Tidal Variation in Field Settling Velocities of Suspended Sediment in a Tidal Channel

Karen Edelvang, Michael Larsen & Morten Pejrup

Edelvang, Karen; Larsen, Michael; Pejrup, Morten: Tidal Variation in Field Settling Velocities of Suspended Sediment in a Tidal Channel. Geografisk Tidsskrift 92:116-121. Copenhagen 1992.

Particles of silt and clay may form large, low density flocs when suspended in salt water. The sediment flocs have settling velocities much higher than the single small particles constituting them and therefore, the flocculation process may strongly influence the transport of cohesive sediment in estuarine environments. As will be described in this paper, the field settling velocities of suspended sediment were investigated in a large tidal channel with tidal current velocities up to 1.3 m/s and depths of about 10 m. The analyses of suspended sediment were made on both bottom and surface samples. For the bottom samples, equivalent median fall diameters in the range 26-98 μm were measured. For surface samples, the range was 15-40 μm. During most of the tidal period, the occurrence of much larger settling diameters near the bottom was due to the suspension of individual sand and silt particles. For the investigated periods, high-tide was the only possible time to observe flocculation influencing the vertical distribution of fine-grained sediment in the water column.

Keywords: *Flocculation, cohesive sediment, estuarine dynamics, tidal channel.*

Karen Edelvang, M.Sc., research fellow, Michael Larsen, M.Sc., research fellow, Morten Pejrup, Ph.D., assoc. prof., Institute of Geography, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K.

Particles of clay and silt have cohesive properties which enable them to coagulate in saline water and form large, low density aggregates. This process is defined as salt flocculation. Flocculation of fine-grained sediment is of great importance in the estuarine environment (Krone, 1972; Pejrup, 1988 and 1991) as it enables even small particles in suspension to be part of the process of accumulation and erosion during a tidal period.

Tidal variation in current velocities during a single tidal period is responsible for the settling lag and scour lag effects (van Straaten & Kuenen, 1957; Postma, 1967). These lag effects cause a sorting of the suspended sediment leading to a concentration of particles and sediment flocs having equivalent fall diameters in the size range 8-100 μm in the inner part of the estuary.

The flocs formed by salt flocculation consist of weakly bounded aggregates with very low densities. Studies by Gibbs (1981, 1982), Kranck (1975, 1981) and Sternberg (1988) show that the size and settling velocities of these flocs can only be estimated using in situ measurements because the fragility of the flocs causes them to break during any mechanical action.

In this study, field settling velocities of the suspended sediment have been measured during two tidal periods. The two sets of data were collected in Ho Bugt under different weather conditions. The selected tidal periods were on October 17, 1989 and July 24, 1990. During both periods, the current velocity, salinity, water temperature and suspended sediment concentration were measured together with the field settling velocities of the fine-grained suspended sediment. The measurements were made from an anchored ship stationed in the main tidal channel of Ho Bugt.

AREA OF STUDY

Ho Bugt is located in the northernmost part of the European Wadden Sea, which extends from Den Helder in Holland to Blåvands Huk in Denmark (fig. 1). Ho Bugt is a 12 km long and 4 km wide bay situated in a semi-diurnal tidal environment with an average tidal range of 1.5 m. As there is no distinct salt-stratification, it may be classified as a well-mixed estuary (Hansen & Rattray, 1966).

Measurements were carried out in Hjerting Løb, the main tidal channel in Ho Bugt, which is the northern branch of the Grådyb tidal inlet. The channel is slightly ebb-dominated. It has an average depth of 10 m and transports about 10% more water out of the area than into it, discharging about 60% of the tidal prism of Ho Bugt. The rest of the water, about 40% of the mean tidal prism, is transported across the tidal flats (Pejrup, 1983).

Moving up the shoaling estuary, the tidal wave is deformed and becomes asymmetrical. Consequently, the ebb-period is prolonged and the flood-period proportionally shortened. However, this effect is not apparent at the measuring site situated in the southern part of Hjerting Løb close to the tidal inlet.

METHODS

The current velocities were measured using a Braystoke 5' impeller current meter with a compass module. Its accuracy for the measurement of current velocity is ± 2 cm/s. Current velocities were measured, every half hour, at five points in a vertical profile above the bottom. In order to minimize the impact of macroturbulence, the readings were averaged over a 100-second-period (Dyer, 1973). The mean current velocity was finally computed as the integral of the five points over the depth.

The water temperature and salinity were measured every half hour, at levels similar to the ones used in the current velocity measurements by a Kent Model 5005 salinometer.

Measurements of the concentration of suspended sediment were carried out using a depth-integrating water-

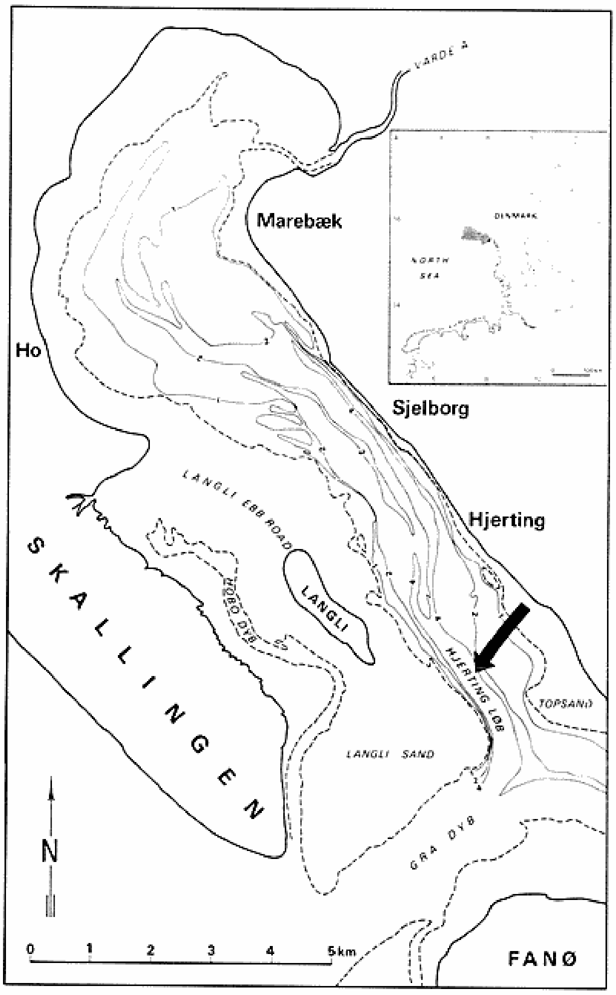

Fig. 1. Map of the investigation area. The arrow indicates the measuring site.

sampler equipped with a one liter bottle. The method is described in Nilsson (1969). Each water sample was filtered in the laboratory using Whatmann GF/F filters with a nominal retention of 0.7 μm. The sediment weight was determined with an accuracy of $\pm$ 0.1 mg. The organic content was determined based on loss of ignition after the filters had been combusted in a muffle furnace at a temperature of 500°C for 4 hours. The filter-weights were corrected by use of control-filters.

The field settling velocities were measured using a Braystoke SK 110 settling tube consisting of a 1 m long perspex tube with a diameter of 5 cm and a total volume of two liters (Pejrup, 1988). The tube was lowered horizontally into the water to the desired measuring depth and subsequently closed by a release messenger, activating the sealing caps at both ends of the tube. The apparatus was lifted horizontally out of the water and placed vertically in a

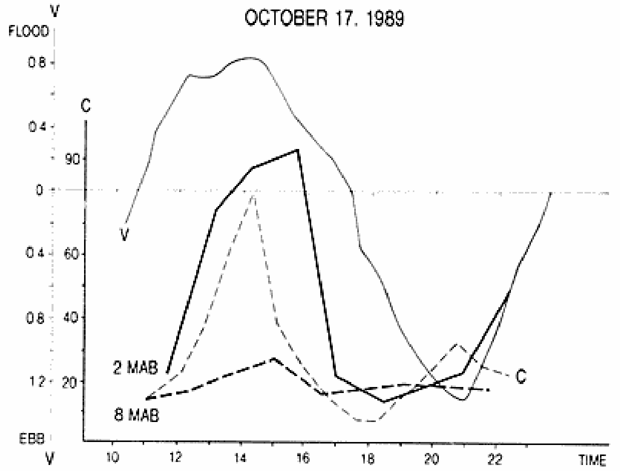

Fig. 2. October 17, 1989: current velocity (V), depth-integrated suspended sediment concentration (C), suspended sediment concentration 2 m and 8 m above bottom (MAB).

matching stand. After this, subsamples were withdrawn from the bottom of the tube at logarithmic time-intervals.

The subsamples were filtered through 0.45 μm millipore CEM filters and the amount of sediment in each subsample determined with an accuracy of $\pm$ 0.1 mg. Thereafter, settling velocities were calculated on the basis of the settling rate of the suspended sediment as a function of time and, finally, the equivalent fall diameter of the sediment was calculated using Stoke's law.

RESULTS

Weather Conditions

October 17, 1989: West-south-westerly wind, 7-9 m/s. The previous day the breeze was fresh, 11-13 m/s from west-south-west.

July 24, 1990: North-westerly wind, 7-10 m/s.

Current Velocities and suspended Sediment Concentration

October 17, 1989: There was no stratification in salinity and temperature. Current velocities are shown in fig. 2. Maximum values were found in the middle of the flood and the ebb period. Generally, the mean current velocity was strongest during the ebb-period with a maximum value of 1.3 m/s because the measurements were carried out in an ebb-dominated channel.

The tidal variation in suspended sediment concentrations, measured with the settling tube, is shown in fig. 2, together with the depth-integrated concentrations. A concentration peak of 78 mg/l was observed in the depth-integrated concentration in the flood period at about 14 h., coinciding with the maximum current velocity. The delay in maximum concentration at the bottom is ex-

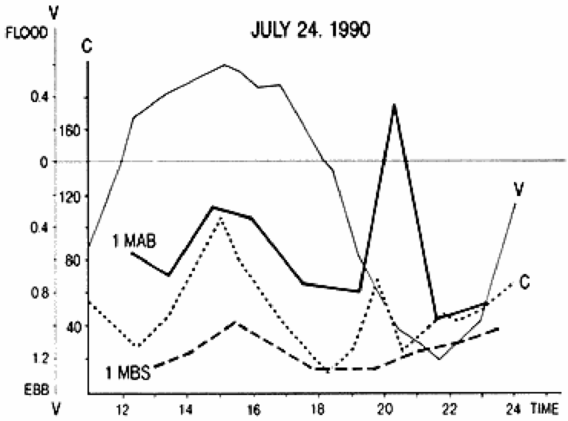

Fig. 3. July 24, 1990: current velocity (V), depth-integrated suspended sediment concentration (C), suspended sediment concentration 1 m above bottom (MAB) and 1 m below surface (MBS).

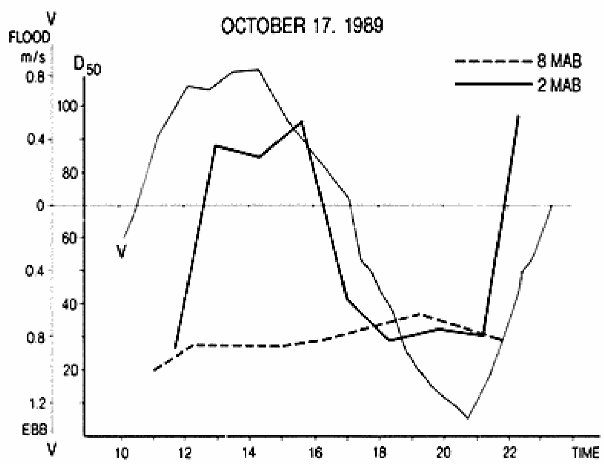

Fig. 4. October 17, 1989: current velocity (V) and D_{50} 8 m and 2 m above bottom (MAB).

plained by the sampling interval of 1½ hours. Probably, maximum concentration occurred at the same time as it did in the depth-integrated samples.

After the high-water slack, there is a settling lag of one hour before minimum concentration occurs and resuspension increases the concentration again. The low sediment concentrations during the ebb period, when current velocities are higher than during the flood-period, are caused by a lack of erodible sediment on the channel floor. It can be seen that the concentration at the surface is constantly low (about 20 mg/l). The concentration at the bottom rises at the end of the ebb-period as the sediment settles at decelerating current velocities.

July 24, 1990: There is only an insignificant vertical variation in salinity and temperature in the water column. The maximum mean current velocity is found in the ebb-period (see fig. 3). In the flod-period the strongest current velocities occur half-way through the period, whereas maximum current velocities are displaced towards low-water during the ebb-period.

The tidal variation in suspended sediment concentrations, measured with the settling tube, is shown in fig. 3 together with depth-integrated concentrations. The peak in the depth-integrated suspended sediment concentration (108 mg/l) in the flood-period coincides with the maximum current velocity. This is also true of the variation in the sediment concentration at the bottom. The settling tube samples show a delay of approximately one hour in the maximum concentration at the surface, which is accounted for by the effects of the turbulent diffusion.

About one and a half hours after high-water slack, there is a resuspension-peak of 63 mg/l in the depth-integrated sediment concentration. It reaches a second maximum of 42 mg/l at maximum current velocity. The concentration of suspended sediment rises at decelerating current velocities throughout the second half of the ebb-period. This phenomenon must be explained by an advective supply of more sediment-rich water from the turbidity-maximum at the estuary head (Pejrup, 1986).

During the flood-period, the vertical variation in the suspended sediment concentration is highest at the bottom where the sediment is being eroded. There is only a minor delay between the maximum values being reached at the bottom and at the surface. This is explained by the time-lag in the turbulent diffusion. The variation follows the variation in mean current velocity.

The ebb-period shows a different pattern. The peak at the beginning of the period at the bottom, originating from resuspension, is not observed at the surface. Near low-water slack, when the concentration is increased, this fact is reflected throughout the water column, indicating that the supply is advective.

Settling Velocities and Grain Sizes

October 17, 1989: A total of 16 settling tube samples were analyzed to determine field settling velocities and equivalent fall diameter. The samples were taken 2 m and 8 m above the bed respectively. A time difference of about 45 minutes between bottom and surface samples was necessary for practical reasons.

The median equivalent fall diameter of the particles at the bottom ranges from 26 to 98 μm as a function of current velocity, with the highest values at the time of maximum velocity in the flood period (fig. 4). The time-lag of about one hour between maximum current velocity and maximum particle diameter can be explained by the difference between erosion and transport velocity. At the surface, the median diameter is almost constant 20-40 μm.

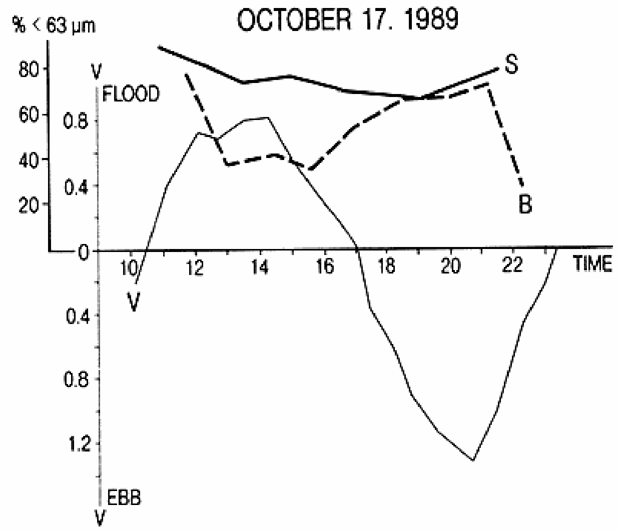

Fig. 5. October 17, 1989: size fraction ⟨63 µm (B = bottom, S = surface) compared to current velocity (V).

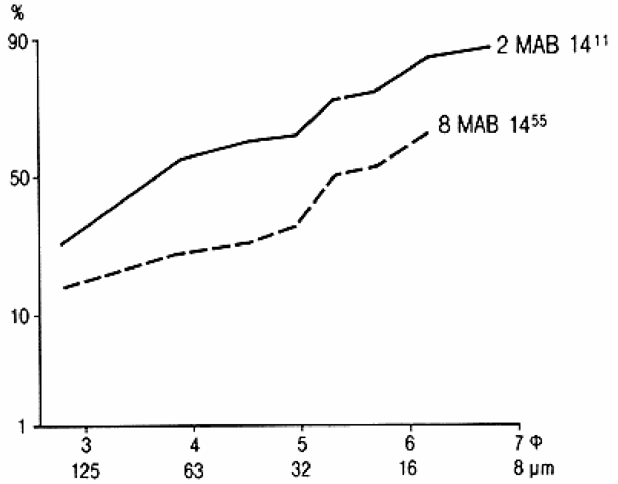

Fig. 7. July 24, 1990: equivalent fall diameter at 14.11 (2 m above bottom) and 14.55 (8 m above bottom).

The sediment part ⟨63 µm at the bottom fluctuates between 27% and 78% during the tidal period, with maximum values at the beginning of the flood-period, fig. 5. At the surface, the variation only ranges from 66 to 88%.

At the beginning of the flood-period, there is a considerable amount of fine sediment. The increase in mean velocity, and thereby bottom shear stress, increases the coarse fraction of the suspended sediment. At maximum current velocity, when erosion is also at a maximum, only 40% of the sediment at the bottom is ⟨63 µm. At high-water slack, there is a small rise to 53% increasing throughout the ebb period until two hours before low-water slack.

At the beginning of the flood-period, when current velocity is accelerating, median grain sizes at the bottom and the surface show an almost similar distribution, as indicated in fig. 6 taken at 11.40 h. and 12.19 h. respectively. This is explained by the fact that the competence of the current is still low. Hence, the curves show similar distributions at both levels. This might be termed the wash-load of the estuary related to the actual weather conditions.

The size distributions of the samples taken at 14.11 h. and 14.55 h. are shown in fig. 7. The velocity has peaked and is decelerating showing velocities similar to the ones

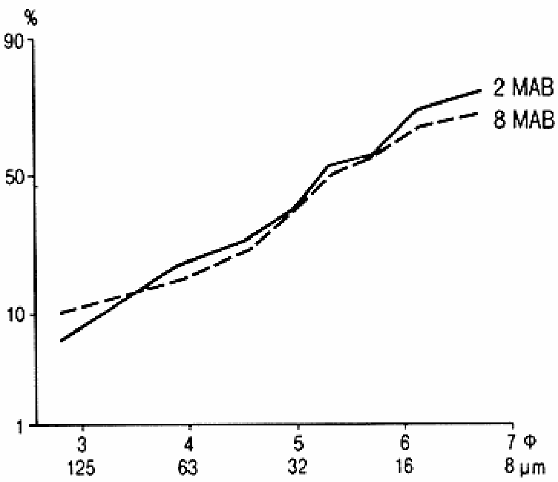

Fig. 6. October 17, 1989: equivalent fall diameter at 11.40 a.m. (2 m above bottom) and 12.19 p.m. (8 m above bottom).

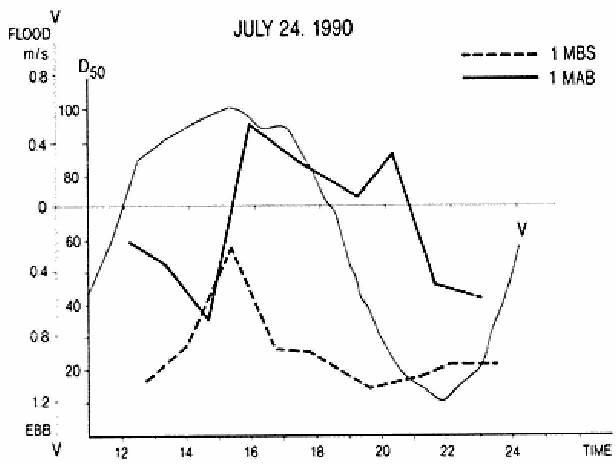

Fig. 8. July 24, 1990: current velocity (V) and D_{50} 1 m above bottom (MAB) and 1 m below surface (MBS).

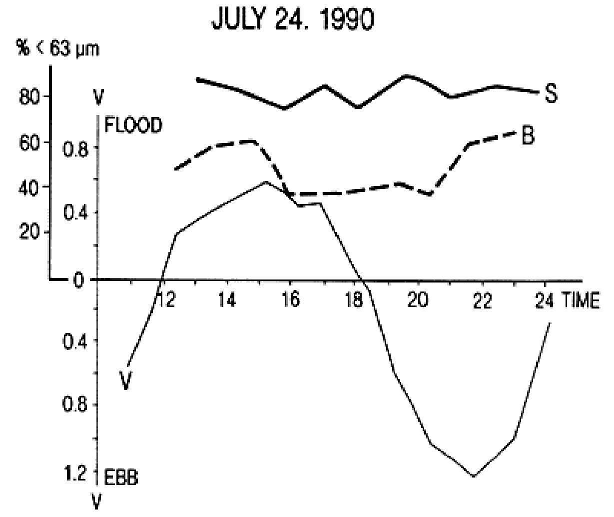

Fig. 9. July 24, 1990: size fraction ⟨63 μm (B = bottom, S = surface) compared to current velocity (V).

about 12 o'clock. However, only 41% of the sediment at the bottom is ⟨63 μm compared to 76% at the surface. The distribution of the fraction ⟨63 μm is almost similar at the surface and the bottom, indicating that the same grain or floc population is present at both levels. The difference in the percentages is caused by the fact that the turbulent diffusion cannot transport the largest particles to the surface.

July 24, 1990: A total of 16 settling tube samples were collected 1 m above the bed and 1 m below the surface respectively. They were analyzed for settling velocities and equivalent fall diameter.

The median equivalent fall diameter at the bottom, shown in fig. 8, fluctuates between 30 and 95 μm. Maximum values are observed during the flood-period, with a delay of one hour between maximum diameter and maximum current velocity. This can be explained by the difference between erosion velocity and transport velocity. The local maximum of D^{50} after high-water slack may be explained by both the resuspension of flocs and the subsequent flocculation, because increased turbulence will enhance these processes at low mean current velocity.

The median equivalent fall diameter at the surface is almost constant, varying between 15 and 25 μm, with a single peak at about the time of maximum current velocity in the flood-period.

Fig. 9 shows the variation in suspended sediment ⟨63 μm. The part of the sediment ⟨63 μm at the bottom increases from 50% to 60% at the beginning of the flood-period. When maximum current velocity is reached, the percentage stabilizes at 40%, where it remains throughout the flood-period and the beginning of the ebb-period.

The maximum size of the sediment is controlled by the competence of the tidal current. At slack, when current velocities are low, the low percentage of sediment ⟨63 μm near the bottom can be explained by flocculation because the small particles are agglomerated, forming larger flocs falling out of suspension. The turbulence of the tidal current during this part of the tidal period is too weak to break up the sediment flocs.

The fraction ⟨63 μm constitutes more than 75% of the total amount of suspended sediment at the surface throughout the tidal period. This is explained by the fact that the turbulent diffusion is unable to carry the largest particles all the way through the water column to the surface.

The total amount of suspended sediment increases at the end of the ebb-period, probably because of an advective supply from the turbidity maximum (Pejrup, 1986) at the head of the bay. 66% of the sediment at the bottom is ⟨63 μm compared to 82% at the surface. The considerable amount of sediment in the fine fraction may be explained by the large content of flocculated particles in the turbidity-maximum.

CONCLUSIONS

With regard to October 17, 1989, the variation of the suspended sediment concentration is linked to the variation in current velocities. Maximum values of suspended sediment concentration are reached during flood. In the course of the ebb-period, when current velocities are higher, there is a deficit in the concentration explained by the lack of erodible sediment on the channel floor. There is no indication of resuspension after high-water slack.

For July 24, 1990, the variation in sediment concentration is also closely related to current velocities. Maximum values are reached during flood. The sediment, which settles at high-water slack, is resuspended about one hour later. At the end of the ebb-period, an advective supply of sediment is carried by the ebb-current from the turbidity maximum at the head of the bay.

The variation of the equivalent fall diameter throughout the tidal period shows that the particle size is governed mainly by current velocity. The median grain sizes of the particles at the bottom are generally much larger (26-98 μm) than those at the surface (15-40 μm), because the largest particles cannot be transported all the way to the surface. There is a time-lag of about one hour between the maximum current velocity and the maximum fall diameter of the particles which can be explained by the differences between erosion velocity and transport velocity. The median fall diameter of the suspended particles stays relatively high at slack, indicating that flocculation takes place in still water when the suspended sediment settles. The resuspension-peak on July 24 is characterized by increased particle sizes, probably because some of the resuspended sediment has been eroded as flocs because turbulence is still moderate at low current velocity.

The results show that the field settling velocities of suspended sediment relate to current velocities during most of the tidal period. Flocculation is insignificant in the investigated tidal channel as it primarily occurs at the time of high-water slack during both measuring periods. This is explained by the fact that, at slack, there is almost no vertical velocity gradient. Hence, the sediment flocs are not destroyed, but are allowed to grow relatively large and settle throughout the water column.

ACKNOWLEDGEMENTS

The funds for this study were provided by the Danish Natural Science Research Council; grant no. 11-7427.

References

Dyer, K. R. (1973): Estuaries: A Physical Introduction, John Wiley & Sons, GB, pp 227.

Gibbs, J. R. (1981): Floc Breakage by Pumps. Journ. of Sed. Pet., Vol. 51, p. 670-672.

Gibbs, J. R. (1982): Floc Breakage during HIAC Light-Blocking Analysis. Environ. Sci. Technol., Vol. 16, no. 5, p. 298-299.

Hansen, D. V. & Rattray Jr., M. (1966): New Dimensions in Estuary Classification. Limnology and Oceanography Vol. 11 no. 3, p. 319-326.

Kranck, K. (1975): Sediment Deposition from Flocculated Suspensions. Sedimentology, Vol. 22, p. 111-123.

Kranck, K. (1981): Particulate Matter Grain-Size Characteristics and Flocculation in a Partially Mixed Estuary. Sedimentology, Vol. 28, p. 107-114.

Krone, R. B. (1972): A Field Study of Flocculation as a Factor in Estuarial Shoaling Processes. U.S. Army Corps Eng., Comm. Tidal Hydraul. Tech. Bull. no. 19, 62 pp.

Nilsson, B. (1969): Development of a Depth-integrating Water Sampler. UNGI rapport no. 2. Uppsala Univ., pp 16.

Pejrup, M. (1983): Et Metodestudium af den Suspenderede Sediment Transport i et Vadehavsmiljø. Medd. Skallinglab., no. 29, 178 pp.

Pejrup, M. (1986): Parameters Affecting Fine-grained Suspended Sediment Concentrations in a Shallow Micro-tidal Estuary, Ho Bugt, Denmark. Estuarine, Coastal and Shelf Science, no 22, p. 241-254.

Pejrup, M. (1988): Flocculated Suspended Sediment in a Micro-Tidal Environment. Sediment. Geol. 57, p 249-256.

Pejrup, M. (1991): The Influence of Flocculation on Cohesive Sediment Transport in a Micro-Tidal Estuary. In: Clastic Tidal Sedimentology. Eds: Smith, D. G., Reinson, G. E., Zaitlin, B. A., and Rahmani, R. A. Canadian Soc. of Petro. Geol. Memoir no. 16, p. 283-290.

Postma, H. (1967): Sediment Transport and Sedimentation in the Estuarine Environment. In: Estuaries. Ed. Lauff, H. G., Washington D. C., p. 158-179.

Sternberg, R. W. et al. (1988): Suspended Sediment Transport under Estuarine Tidal Channel Conditions. Sed. Geol., Vol. 57, p. 257-272.

Van Straaten, L. M. J. U. & Kuenen, P. H. (1957): Accumulation of Fine-grained Sediments in the Dutch Wadden Sea. Geologie en Mijnbouw (NW. Ser.) Vol 19, p. 329-354.

increased particle sizes, probably because some of the resuspended sediment has been eroded as flocs because turbulence is still moderate at low current velocity.

The results show that the field settling velocities of suspended sediment relate to current velocities during most of the tidal period. Flocculation is insignificant in the investigated tidal channel as it primarily occurs at the time of high-water slack during both measuring periods. This is explained by the fact that, at slack, there is almost no vertical velocity gradient. Hence, the sediment flocs are not destroyed, but are allowed to grow relatively large and settle throughout the water column.

ACKNOWLEDGEMENTS

The funds for this study were provided by the Danish Natural Science Research Council; grant no. 11-7427.

References

Dyer, K. R. (1973): Estuaries: A Physical Introduction, John Wiley & Sons, GB, pp 227.

Gibbs, J. R. (1981): Floc Breakage by Pumps. Journ. of Sed. Pet., Vol. 51, p. 670-672.

Gibbs, J. R. (1982): Floc Breakage during HIAC Light-Blocking Analysis. Environ. Sci. Technol., Vol. 16, no. 5, p. 298-299.

Hansen, D. V. & Rattray Jr., M. (1966): New Dimensions in Estuary Classification. Limnology and Oceanography Vol. 11 no. 3, p. 319-326.

Kranck, K. (1975): Sediment Deposition from Flocculated Suspensions. Sedimentology, Vol. 22, p. 111-123.

Kranck, K. (1981): Particulate Matter Grain-Size Characteristics and Flocculation in a Partially Mixed Estuary. Sedimentology, Vol. 28, p. 107-114.

Krone, R. B. (1972): A Field Study of Flocculation as a Factor in Estuarial Shoaling Processes. U.S. Army Corps Eng., Comm. Tidal Hydraul. Tech. Bull. no. 19, 62 pp.

Nilsson, B. (1969): Development of a Depth-integrating Water Sampler. UNGI rapport no. 2. Uppsala Univ., pp 16.

Pejrup, M. (1983): Et Metodestudium af den Suspenderede Sediment Transport i et Vadehavsmiljø. Medd. Skallinglab., no. 29, 178 pp.

Pejrup, M. (1986): Parameters Affecting Fine-grained Suspended Sediment Concentrations in a Shallow Micro-tidal Estuary, Ho Bugt, Denmark. Estuarine, Coastal and Shelf Science, no 22, p. 241-254.

Pejrup, M. (1988): Flocculated Suspended Sediment in a Micro-Tidal Environment. Sediment. Geol. 57, p 249-256.

Pejrup, M. (1991): The Influence of Flocculation on Cohesive Sediment Transport in a Micro-Tidal Estuary. In: Clastic Tidal Sedimentology. Eds: Smith, D. G., Reinson, G. E., Zaitlin, B. A., and Rahmani, R. A. Canadian Soc. of Petro. Geol. Memoir no. 16, p. 283-290.

Postma, H. (1967): Sediment Transport and Sedimentation in the Estuarine Environment. In: Estuaries. Ed. Lauff, H. G., Washington D. C., p. 158-179.

Sternberg, R. W. et al. (1988): Suspended Sediment Transport under Estuarine Tidal Channel Conditions. Sed. Geol., Vol. 57, p. 257-272.

Van Straaten, L. M. J. U. & Kuenen, P. H. (1957): Accumulation of Fine-grained Sediments in the Dutch Wadden Sea. Geologie en Mijnbouw (NW. Ser.) Vol 19, p. 329-354.