The behaviour of fines released due to dredging
A literature review

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Abstract

In 2001 a DIOC-project was started at Delft University of Technology on the dispersion of fines during sand mining. In this project the behaviour and spreading of fines, which are released through the overflow of a dredging ship, is studied. Laboratory and field studies will be carried out to determine the behaviour and spreading of the fines. However, before any experiments are carried out, a literature study is done to determine the main focus of the subsequent research. This literature study is presented herein. It discusses the whole cycle of dredging, the release of sediment in the water, behaviour of sediment in the water column, sedimentation, erosion and impact on ecology. In the end it is decided that the subsequent research shall focus on two subjects, namely the hindered settling of sand/mud mixtures and the sea/bed interaction.

Chapter 1

Introduction

1.1 Problem definition and objective

Because of the shortage of building plots and the ever increasing demand for sand for building purposes in the Netherlands, studies were started to investigate the possibilities of constructing building plots in, and extract sand from the North Sea. When constructing these building plots and extracting the sand, the amounts of dredged material shall largely exceed the amounts normally dredged in a year. Consequently the amount of sediment that is resuspended and released in the water column will be substantially higher than the current rate. There are several ways in which sediment gets in the water column. First, there is the sediment that gets resuspended by the dredging work of the suction heads. Secondly, the overflow of dredging ships puts a substantial amount of dredged sediment back into the water. Thirdly, some sediment gets lost through the doors in the hull of the ship during transport. Fourth, during the dumping of dredged material some sediment will be stripped from the main bulk of sediment. Fifth, due to the cleaning of the suction pipes and the hopper, some sediment is released into the water, which is called AMOB. Most of the sediment that is released in one of these five ways is fine sediment, also called fines (D$< 63\mu$m). The fines that are resuspended and released during these dredging operations can have a large impact on the biotic system. In this research the emphasis will lie on the fines that are released through the overflow.

The fines released from the overflow can behave in several ways. They can behave as a density current, in which case a cloud of fines moves over the seabed and may settle in the near vicinity of the dredging vessel. In this case the turbidity in the water will not alter much, but benthic species can get covered with mud. However, this mud layer on the bottom can get eroded after a while, leading to large amounts of fines in the water column over a large distance. Another possibility is that the fines mix with the water as soon as they leave the overflow. This will result in an increase in turbidity throughout the water column and a possible subsequent reduction in light penetration and primary production.

Few experiments were done on sand/mud mixtures. Therefore it is not known at present how fines filtrate into the seabed and when fines are eroded again. This however is an important issue when large amounts of dredged material, consisting mainly of fines, are spilled from the dredging ship and settle on the seabed. The grain size distribution may be altered in such a way that the fines prevail and create an erosion-resistant layer. During high energetic conditions these layers of fine material can be eroded, which results in a high turbidity, probably over a large area.

Thus, fines that are released through the overflow can behave in several ways in the watercolumn, finally resulting in sedimentation on the bed. The quantity and quality of fines that are released during dredging and the fines that can get resuspended are not known. Therefore a research is started, initiated by DIOC WATER. The objective of this research is to determine the way fines disperse from an overflow, the behaviour of plumes and clouds of fines (sand/mud mixtures) and the mechanisms leading to settling, consolidation and erosion of overflow sediments on the bed, all in the mid field area (a few hundred metres from the dredging ship). Research questions to be addressed shall deal with the settling of overflow plumes, the interaction with the sea water and the exchange between the water phase and the bed. Laboratory experiments and field experiments will be done to answer these research questions.

1.2 Objectives of the literature review

This study is started with a literature review, which is carried out to summarise the knowledge on aspects dealt with in the research. It describes the whole cycle from dredging and overflowing techniques to the subsequent overflow plumes, the behaviour of these overflow plumes, the material that is dealt with, the interaction with the seabed and the repercussions on the environment.

Chapter 2

Dredging

Dredging is the removal of bed material (either rock, gravel, sand or mud) out of the water and placing these sediments on a different site. It has been done for thousands of years, beginning along the Nile, Euphrates, Tigris and Indus rivers as described by Gower (1968) in Herbich (2000). These early forms of dredging were carried out by primitive methods with spades and baskets. The Roman infantry, slaves, and prisoners of war were often employed in large-scale excavation works (Herbich, 2000). Since then, dredging has come a long way.

2.1 Dredging vessel

The methods used nowadays are quite different from those in the early days. The type of ship that is often used for large dredging and landreclamation works is the Trailing Suction Hopper Dredger, referred to as TSHD. A TSHD is a hydraulic dredger, which means that the material is surfaced hydraulically. TSHD's are suitable for loose grained material and are, by far, the best-suited dredgers for offshore work. They come in sizes up to 33.000 m^3 of hopper capacity.

When a dredging cycle is started, a sediment/water mixture is brought to the ship by a draghead, which varies with the type of material, and through a suction pipe. The sediment settles once inside the hopper. The precise method of dredging is different for most cases. The method merely depends on the dredged material and on the crew. For example, during sand dredging the inside water level before dredging is often levelled with the outside water level. In contrast, during mud dredging the hopper often starts empty. During dredging and the filling of the hopper, the excess water, often in combination with the fines, has to be removed through the overflow. Often the overflow level is positioned at the expected sand level. An extra lowering of the overflow is then not necessary. Another possibility is to dredge with a constant tonnage system. In the latter case the overflow drops slowly during the dredging process. Filling of the hopper continues until overflow losses are becoming too large. This is not only important from an economical point of view, but also from an ecological. Large overflow losses will result in increased turbidity in the watercolumn and therefore result in reduced light penetration and possible burial of marine organisms.

As to prevent overflow losses becoming too large, turbulence in the hopper must be kept at a minimum to allow the material to settle. Therefore the overflow weir is constructed opposite to the inlet of the dredged material (Herbich, 2000). Furthermore the inlet system affects the amount of sediment that is kept in suspension by turbulence. To limit turbulence production, the sediment/water mixture should be pumped into the hopper at low velocity, allowing the material to spread over the whole width of the hopper. Due to the low inflow velocities erosion of the sandbed will be low and the residence time of the mixture will be large (Boot, 2000). There is a large variety of inlet configurations, all having different effects on the behaviour of the inflow. They can be distinguished between deep loaders (discharging the mixture near the bottom of the hopper as to reduce turbulence as much as possible), diffusers (a large lateral spreading), or fishtails (gives an even distribution of the mixture over the hopper area). Furthermore chains and bulkheads in the hopper can reduce the velocities of the mixture.

2.2 Sedimentation in a hopper and overflow losses

Research on sedimentation in hoppers has been carried out by Van Rhee (2001b), Van Rhee (2001a), Ooijens (1999) and Miedema & Vlasblom (1996), amongst many others. Their models, that predict sedimentation in a hopper and overflow losses, are based on the Camp (1946) model, a settling basin theory model, originally developed for waste water treatment. The Camp (1946) model uses a strongly simplified flow field (no vertical flow) and a constant flow depth, as the settled material in waste water treatment plants gets mechanically removed from the settling tank. Miedema & Vlasblom (1996) used this Camp model as the basis of their model, but also incorporated sorting, erosion, hindered settling and the influence of a rising sandbed. Ooijens (1999) added dynamics to this model. The time effect was added by regarding the hopper as an ideal mixing tank. The concentration in the hopper according to Miedema & Vlasblom (1996) is always equal to the inflow concentration and the outflow concentration responds instantaneously on the calculated settling efficiency. However, in Ooijens (1999) the calculated concentration in the hopper is used for the settling efficiency calculation. According to Van Rhee (2001b) this extension was an improvement, since it enabled for instance the influence of the overflow level variation on calculations.

An important quantity during the loading process is the overflow loss. Two different definitions of this quantity are being used. The loss can be defined as the ratio of the outflow and inflow sand flux at a certain moment, or as the ratio of the total outflow and inflow volume (Van Rhee, 2001b). The overflow flux is defined as:

$$OV_{flux}(t) = \frac{Q_o(t)C_o(t)}{Q_i(t)C_i(t)} \tag{2.1}$$

The cumulative overflow loss is defined as:

$$OV_{cum}(t) = \frac{\int_0^t Q_o(t)C_o(t)\mathrm{d}t}{\int_0^t Q_i(t)C_i(t)\mathrm{d}t} \tag{2.2}$$

In which Q is the discharge and C the volume concentration. The indices i and o relate to the inflow and outflow (Van Rhee, 2001b). When taking into account sedimentation processes in the hopper, the overflow losses can be described as a function of the grain size (D_{50}), the grain size uniformity (cu) which is the D_{60}/D_{10} ratio , the average flow (Q_{ave}), concentration in the hopper (C_v) and the height of the bed in the hopper (h_s) (Ooijens, 1999). This results in an overflow loss (OV) of:

$$OV = f(C_v, Q_{ave}, h_s, D_{50}, cu) \tag{2.3}$$

In Equation 2.3, however, local processes, like erosion and local flow and concentration, are neglected and the model assumes a steady state (Ooijens, 1999). As Ooijens (1999) adds dynamics to the Camp model, one should consider the development in time by dividing the process in different loading stages and therefore changes in the overflow losses. Ooijens

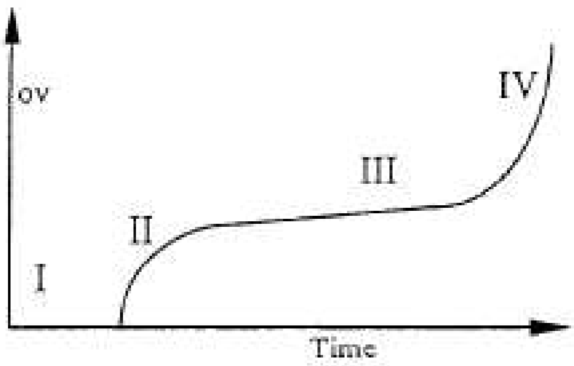

Figure 2.1: Phases in the overflow loss. After Ooijens (1999).

(1999) and many others distinguish four stages (when loading with a constant flow and concentration) as shown in Figure 2.1:

I Before the overflow level is reached there is no outgoing flow. Consequently there are no overflow losses. In this phase the horizontal velocity in the hopper is low, which means a good sedimentation of the grains. The average concentration of the mixture in the hopper (C_v) will be relatively low when the overflow is reached. The volume during this phase is constant.

II This stage is a transition stage between I and III. When the overflow level is reached, overflowing starts and the velocity in the hopper will increase. The increasing average velocity causes a decreasing settling efficiency. The average concentration in the hopper slowly increases, causing a decreasing settling velocity and an increasing overflow loss. The volume during this phase will decrease.

III A steady-state phase emerges in which only the volume of the mixture and the horizontal velocity will slowly increase. The overflow losses are quite constant in this phase, until the scouring velocity is reached.

IV The horizontal velocity in the hopper will increase and scouring will dominate the settling process when the free volume in the hopper decreases. This increases the overflow losses excessively and decreases the volume in the hopper.

The foregoing theory on behaviour during several different stages of the overflow is however already outdated. Van Rhee (2001b) carried out experiments in a rectangular laboratory flume with a glass side wall, through which flow patterns could be monitored.

According to Van Rhee (2001b) the hopper area can be divided into five different sections (Figure 2.2):

1. the inflow section

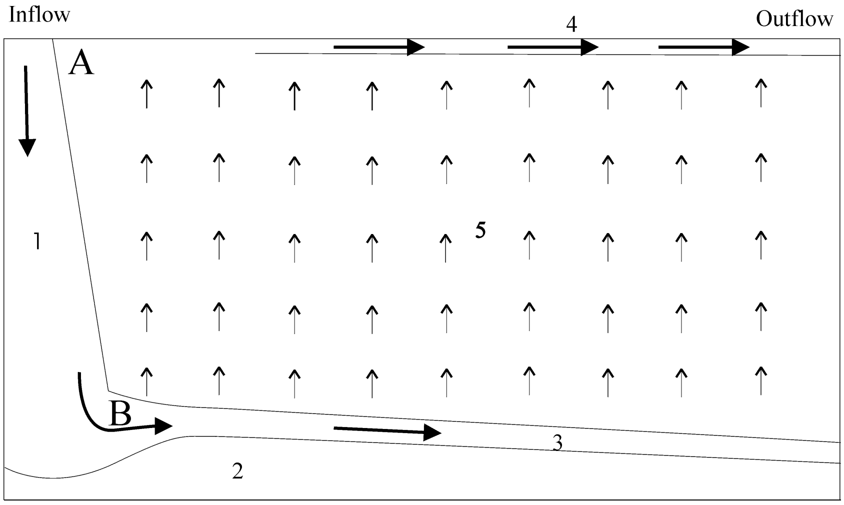

Figure 2.2: Schematic overview of flowfield in hopper (Van Rhee, 2001b). A is the inflow section and B is the density current.

2. the settled sand or stationary bed
3. the density flow over the settled bed
4. the horizontal flow at the surface towards the overflow
5. the suspension in the remaining area

In the inflow section (A), the incoming mixture flows towards the bottom and forms an erosion crater and density current (B). From this current sedimentation will take place (the largest particles will settle first) which leads to a rising sand bed. The part of the incoming sediment which does not settle (the finer sediment) will move upward into suspension. At the water surface the vertical supply of water and sediment creates a horizontal flow towards the overflow section. The overflow process will be continued until the hopper is completely filled with sediment, or when the overflow losses will grow to an unacceptable level. The particle size distribution of the inflow and the outflow section were measured by Van Rhee (2002). The particle size distribution of the inflow was found to be reasonably constant, but the overflow samples showed a large variation of the particle size distribution, becoming coarser in time. The increasing grain diameter in the overflow is related to the increasing concentration in the overflow. Due to hindered settling the settling velocity decreases with concentration and therefore larger grains remain in suspension and are removed with the overflow (Van Rhee, 2002). Also the erosion of the bed at the end of the overflow cycle adds coarser material to the overflow.

On the basis of the observed flow field and grain size distributions Van Rhee (2001b) developed a numerical 1DV model to determine the overflow losses. Instead of the horizontal one-dimensional approach of the Camp-like models with a horizontal supply of sand on one side and overflow on the other, this model is a vertical model, supplying sand from the bottom (fed by the density current in the hopper) and the overflow is located at the top.

Furthermore he implemented the influence of the hopper load parameter and the mutual interaction of the different grain sizes of the particle size distribution in a relative simple way, whereas in the Camp model every fraction is calculated independently. Van Rhee (2001b) then compared the numerical model with one-dimensional tests in a sedimentation column and with model hopper sedimentation tests. It showed a good agreement between the model and the experiments. This does not guaranty good agreement between the model and measurements in real hoppers because of the different scales and because horizontal transport and erosion is not accounted for in the 1DV model. Therefore Van Rhee (2002) extended the 1DV model to a 2DV model. A boundary condition at the interface between the settled sediment and the mixture above had to be formulated for the numerical model. Van Rhee (2002) did some sedimentation tests in the laboratory and found an empirical relation between the bed shear stress and the reduction of the sedimentation flux. This empirical relation was built in the two-dimensional model, after which the model was validated and found to agree well with laboratory and (limited) prototype measurements.

2.3 Conclusion

Sedimentation in a hopper is a complex process, changing with sediment concentration, type of sediment, and in time. A simple 1DV model is developed by Van Rhee (2002), only taking into account the vertical movement of water and sediment. This model can be used in further research in order to make an estimate of the overflow losses and the grain size distribution. A more accurate estimate of the amount of overflow loss and the grain size distribution can thereafter be made with the 2DV model. The results of the 1DV and 2DV model can be used as boundary conditions for the mid field mud dispersion research. With these boundary conditions the types of plumes in the water and the resulting impact on the environment can be predicted.

Chapter 3

Mud

The sediment-water mixture that leaves the overflow exists of sand and finer material . Most of the sand will settle in the near vicinity of the ship. The fines however can behave in a different way, depending on their composition.

3.1 Constituents

Mud is defined as a sediment mixture with particles smaller than 63 μm. It consists of organic and anorganic components, water and sometimes gas. The anorganic fraction contains quartz, feldspar, clay minerals, calcite, dolomite, hydroxides, silicates, sulfides and small fractions of other minerals (Groenewold & Dankers, 2002). The organic material in mud consists of living and dead material as bacteria and remnants or products of fytoplankton, bentic algae, faecel pellets, peat and macromolecules produced by bacteria (eps and proteins) . The amount of organic material in mud strongly depends on the source and season. In intertidal areas it may amount to 10-20% of the dry weight of the sediment and due to the high amounts of adsorbed water even 70-90% of the wet weight (Groenewold & Dankers, 2002). These values are considerably lower in the North Sea seabed.

The water and organic material content decreases due to drying and consolidation of the sediment layers. Therefore older mud differs strongly from the biologic active mud that lays at the surface. The resuspension of old mud layers due to dredging activities may thus have a different impact on the environment than the resuspension of the top-active layer (Groenewold & Dankers, 2002).

3.2 Structure

The clay fraction, the fraction $< 2\mu$m, is the most important substance of mud as it exhibits typical properties. Two important properties of clay are plasticity and cohesion (Partheniades, 1980). Plasticity is the property of a clay mass to undergo substantial permanent deformation, at the proper water content, under stresses, without breaking (Partheniades, 1980). Cohesion is the property of a material to stick or adhere together.

Clays are composed essentially of one or more members of a small group of clay minerals. These minerals have predominantly crystalline arrangements; i.e. the atoms composing them are arranged in definite geometric patterns. Clayey materials can then be considered to be made up of a number of these clay minerals stacked on each other in the form of a sheet or layered structure (Partheniades, 1980).

Chemically, clay consists of silicates of aluminium and/or iron and magnesium. These minerals form two fundamental building blocks which compose the clay mineral. The silicon-oxygen sheet is one of these building blocks. It is formed by a SiO4 tetrahedron. The other building block is the Al- and Mg-O-O-H sheet, which forms an octahedron. With these building blocks clay minerals are formed. Smectites, Illites and Kaolinites are the most common. The differences of these clay minerals arise due to the different degree of weathering. Kaolinite is the youngest clay mineral. With increasing weathering time it changes via Illite to Smectite.

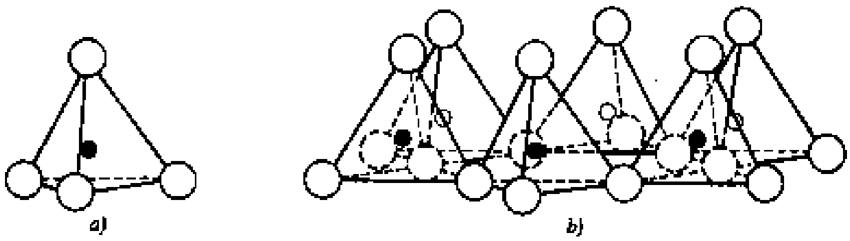

Figure 3.1: Silica tetrahedron (a) and silica tetrahedra (b) arranged in a hexagonal network. After Mitchell (1993)

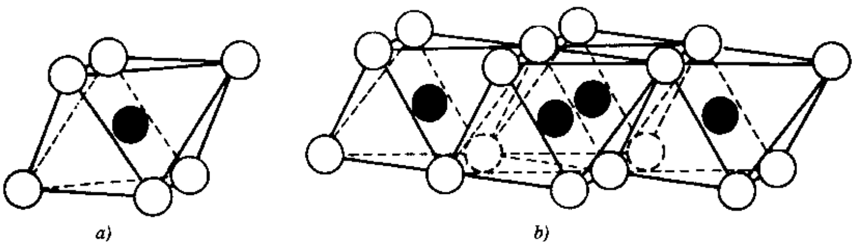

Figure 3.2: Octahedral unit (a) and sheet structure of octahedral units (b). After Mitchell (1993)

Smectites are known as expanding three-layer clays and have a structure that consists of an octahedral sheet sandwiched between two silica sheets. A stack of such layers is forming a Smectite particle. Minerals of the Smectite group are Montmorillonite, Hectorite and Laponite. Laponite has Lithium instead of Aluminium in its network and it forms peculiar large transparent flocs. Smectites can double in volume, due to osmotic swelling (Mitchell, 1993) and the intrusion of water molecules between the layers. Another characterisation of Smectites is the extensive substitution of aluminium and silicon ions by magnesium, iron, zinc and nickel; or aluminium in the silicon case.

Illite clays form a different class of the three-layer clays. These clays are distinguished from the Smectite clays primarily by the absence of inter layer swelling with water. The minerals muscovite and phlogopite, for instance, are minerals of the Illite group (De Wit, 1995).

In contrast with Illites and Smectites, Kaolinites have an almost perfect 1:1 layer structure. The main difference between the various species of Kaolinites is a difference in the layer stacking geometry. Members of this group are Kaolinite, Dictite, Nacrite and Hallogsite. The Kaolinite clays are non-expandable in water.

3.3 Forces between clay minerals

There are several forces that act between clay minerals. Some of them will be discussed here. The Van der Waals forces are secondary valence forces of an electro-chemical nature. They are generated by the mutual influence of the motion of electrons of the atoms and they are always attractive. The attractive potential of Van der Waals forces between two atoms is inversely proportional to the 7^{th} power of the distance. In order to become effective, particles must come very close to each other (Partheniades, 1980).

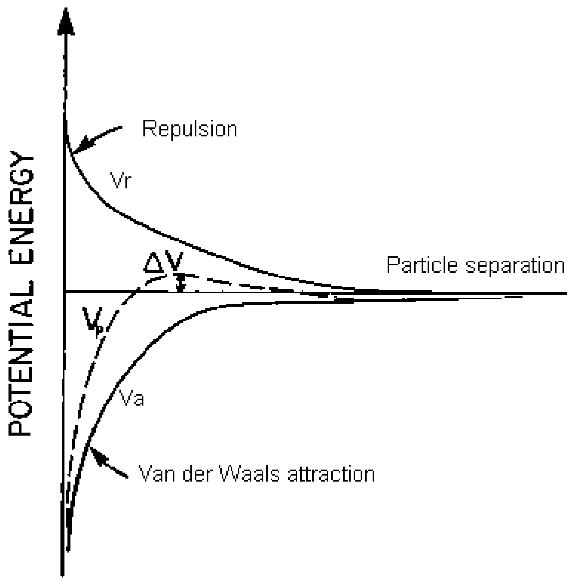

Figure 3.3: The interaction between Van der Waals force and repulsive forces. After Partheniades (1980)

In contrast to the Van der Waals forces, which are generated within the mass of the matter, there are a number of other repulsive and attractive forces generated by electric charges on the surface of particles. On clay minerals these surface charges are negative. They can be caused by isomorphous substitution, where an atom of positive lower valence replaces one of higher valence resulting in a deficit of positive charge and an excess of negative charge. Such substitution takes place in Montmorillonites but very rarely in Kaolinites. Isomorphous substitution is a permanent feature of the mineral inducing a constant negative charge which does not depend on the chemical characteristic of the ambient fluid. Another cause of electric surface forces is the preferential ion adsorption on particle surfaces. This ion adsorption increases the electro-negativity of the particle. This charging process requires the presence of ion electrolyte containing the kind of ions that can be adsorbed on the surfaces of the particle.

Negatively charged clay minerals in water will attract ions of the opposite charge, called ”counter ions”, to compensate its own electric charge. Thus, a clay particle will be surrounded on either side by a diffused layer of counter-ions. This layer is called the diffusive double layer. It neutralises the negative charge of the minerals, so that particles can come at a closer distance from each other and the Van der Waals force may be able to bind the particles together.

The net interaction between two particles is found by adding the repulsive and the attractive energy (Figure 3.3). According to De Wit (1995) it can be shown that there is almost no repulsion at high electrolyte concentrations, as the double layer is strongly compressed, which results in a maximal particle coagulation rate.

3.4 Flocculation

The clay minerals mentioned before form, together with organic material and fractions of silt, primary particles. These primary particles aggregate to form flocs, which can break-up again. The process of aggregation and break-up is called flocculation.

Aggregation of particles occurs when two particles collide and stick together. The amount of aggregation depends therefore on the frequency of collisions, the efficiency of the collisions in sticking together and the number of particles. Particle collisions occur due to Brownian motion of particles, turbulence within the suspending liquid and differential settling of the suspended particles (Van Leussen, 1994; Winterwerp, 1999). The collision frequency then depends on these mechanisms and on the concentration. The effect of waves on flocculation is not known. Probably it is not of significance as the turbulence produced by waves is of a larger scale than the motion of the particles. The shear rate produced by turbulence, on the other hand, may disrupt the flocs again, causing floc breakup (Winterwerp, 1999).

The different mechanisms for flocculation result in different structures of the aggregates. In literature the term perikinetic flocculation is used for the flocculation caused by the Brownian motion. It is found that the aggregates formed in this manner have a ragged and weak structure. However aggregates formed by orthokinetic flocculation, i.e. flocculation controlled by turbulence, tend to be spherical and relatively strong. The flocs formed by differential settling have a low density and are very weak (Van Leussen, 1994).

The efficiency of the collisions in sticking together is determined by the particle charge, the ion concentration in the water and by biopolymers and organic coating on the particles. An increasing salinity, increasing the ion concentration, is therefore thought to be an important flocculant. The increasing electrolyte concentration due to salt would result in a compression of the diffusive double layer. This thinner layer then would diminish the repulsive forces between particles, leading to a more intensive flocculation. Van Leussen (1994) however did a literature research on salt flocculation finding out that often salt does not seem to enhance flocculation but decreased flocsizes at the saltwater contact.

Organic coatings on suspended particles can have a major influence on the particle surface charge. It is believed that organic material can alter the charge of even strongly positively charged particles. Biopolymers can significantly alter the collision efficiency of particles. Here the binding mechanism is not the reduction of the surface potential of the particles but polymers that are adsorbed on the surfaces of the particles. When the particles meet each other, bridges will be formed between the particles and thus an aggregate will be formed. Optimum aggregation occurs when a certain fraction of available adsorption sides on the surface of the particles is bridged by polymers. If too little places are occupied by polymers, inter-particle bridging may be weakened and inter-particle bridges are broken by shear arising from fluid motion. On the other hand, as more sites are covered, free places available for formation of bridges become limited and particle aggregation is hindered (Van Leussen, 1994).

From the preceding section, it can be stated that physical processes mainly determine the collision frequency and that chemical and biological processes mainly determine the stickiness. Not all collisions will result in aggregation as the sticking efficiency is not large.

Winterwerp (1999) concluded after reviewing different papers that Brownian motion and differential settling are probably small in estuarine and coastal environments. Therefore, he focussed on the effect of turbulence. Dyer (1989) proposed a conceptual model of floc size on the basis that flocculation is mostly determined by concentration and by shear stress due to turbulence. Figure 3.4 shows an increase in flocsize with concentration till a certain point.

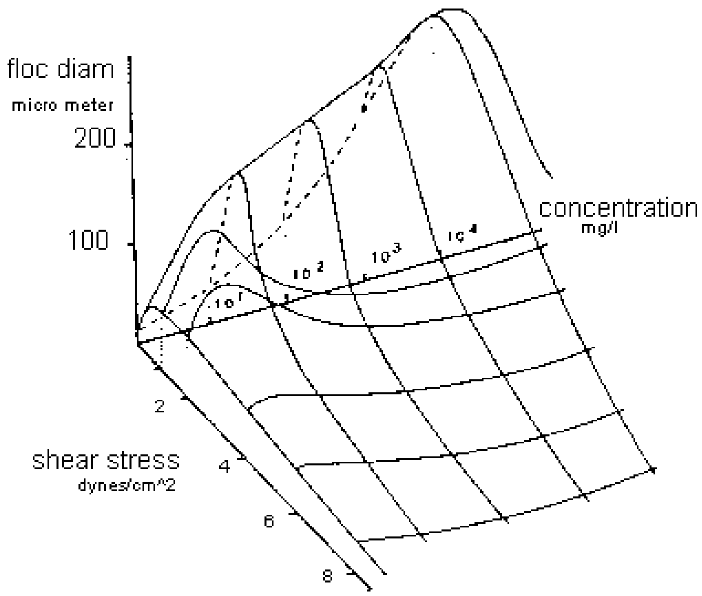

Figure 3.4: Conceptual flocculation diagram. After Dyer (1989)

This increase in flocsize is due to the higher occurrence of collisions with higher concentrations. According to Dyer (1989), increasing shear stresses initially cause increasing flocsizes until floc break-up due to fluid shear becomes more important and floc sizes decrease again. However, in this model of Dyer (1989), the collision efficiency, e.g. salinity and biopolymers, are not taken into account. Winterwerp (1999) restricted himself to the effect of shear stresses on the flocculation process of cohesive sediment. All secondary effects, such as the influence of the particles on the turbulence structure itself, are omitted. He compared the maximal settling velocity results from the model with settling column experiments as is shown in Figure 3.5. On the vertical axis $w_{s,max}$ is divided by c which is almost equal to the grain size diameter (D) . The solid line represents the model at a height of 4, 2 and 1 metre, showing an increasing grain size diameter with G (dissipation parameter) at small G, and a decrease at large G. The dissipation parameter G is equal to the shear stress. Figure 3.5 shows a sim-

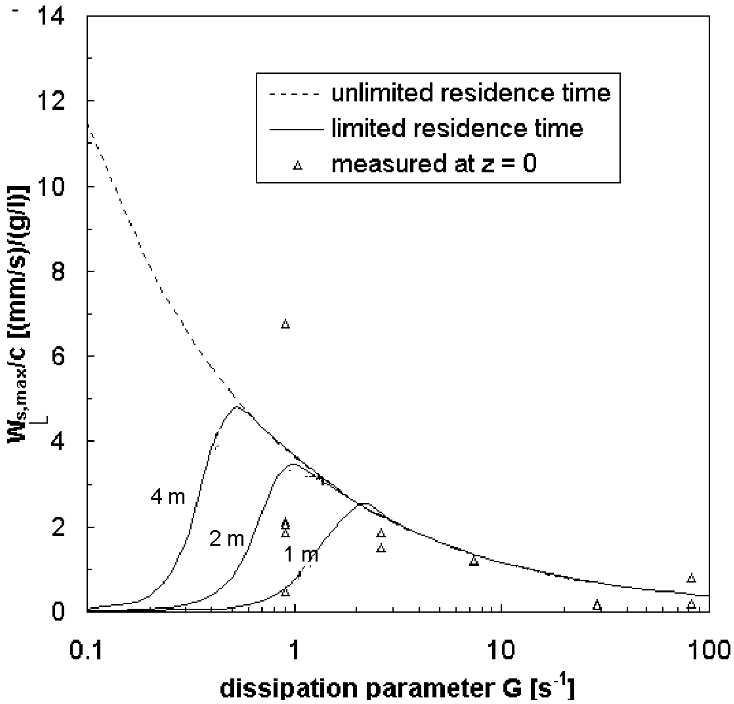

Figure 3.5: Variation of the grain size diameter (vertical) with the shear stress (horizontal). After Winterwerp (1999)

ilar behaviour as Figure 3.4. The dashed line in Figure 3.5 represents the settling velocity under equilibrium conditions. At small shear stresses flocs can not reach this equilibrium. According to Figure 3.4 the floc size increases significantly at low shear stresses. This results in an increasing settling velocity. The bottom of the settling column will be reached before the equilibrium size is reached. The residence time of the flocs in the column thus becomes the limiting factor. At large shear stresses, this is not a problem anymore. In that case the flocs do not get very large and their residence time in the water column is large enough to reach equilibrium size.

3.5 Flocs and fractals

Krone describes flocs as a hierarchical structure of sub-flocs. The first order is a flocculi, consisting of primary particles. A second order floc is a conglomerate consisting of several first order flocs. A third order floc consists of second- and lower order flocs and so on. The structure of a floc according to Krone is shown in figure 3.6.

Krone introduced this concept of order of aggregation, and showed experimentally that floc density, yield strength and viscosity depend on the order of aggregation. He suggested that the structure of the floc is more or less dependent on the exponent, i.e. the fractal dimension or Hausdorff dimension.

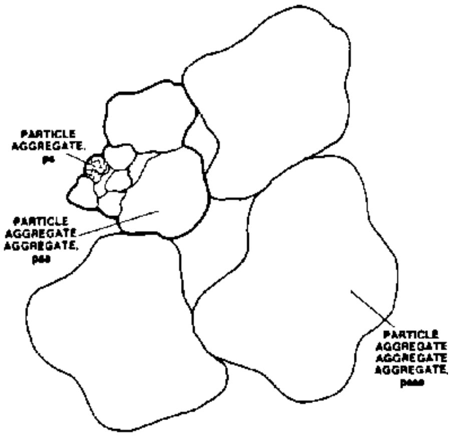

Figure 3.6: Schematic representation of various order flocs in a clay suspension system. After Krone

3.6 Settling velocity of flocs

Basically, the fall velocity is a behavioural property. The terminal fall velocity, $W_{s,r}$, of a sphere is the fall velocity when the fluid drag force on the particle is in equilibrium with the gravity force. Stokes found for spherical, massive particles, (sand) in the Stokes' regime:

$$W_{s,r} = \frac{(\rho_s - \rho_w) g D^2}{18\mu} \tag{3.1}$$

However, this cannot be used on mud flocs, as they are not spherical, their density is not known and they sometimes exceed the applicable range.

The settling velocity of mud flocs is a function of their size D and differential density $\Delta\rho_f$, i.e. the excess density relative to water. Due to aggregation effects, flocs form with relatively small $\Delta\rho_f$; typical values for $\Delta\rho_f$ are in the order of 50 to 300 kg/m^3 (Winterwerp, 1999). Winterwerp (1999) found for mud flocs with a fractal structure to yield an implicit formula for the settling velocity of single mud flocs in still water ($w_{s,r}$):

$$w_{s,r} = \frac{\alpha}{18\beta} \frac{(\rho_s - \rho_w) g}{\mu} {D_p}^{3-n_f} \frac{D^{n_f - 1}}{1 + 0.15 {Re_p}^{0.687}} \tag{3.2}$$

Where α and β are a shape factor of the sediment, ρ_s is the density of primary sediment particles, ρ_w is the density of water, g is the acceleration of gravity, μ is the dynamic viscosity, D_p is the diameter of primary mud particles, n_f is the fractal dimension of mud flocs and Re_p is the particle Reynolds number. $n_f \approx 2$, which shows that the fall velocity is proportional with the floc diameter (D) and not with D^2 as in Stokes' formula. It is assumed that fluid flows around, and not through the particles. This in contrast to Johnson *et al.* (1996) who treated flocs as permeable particles, where the settling velocity is affected by the flow through pores of the flocs. Winterwerp (1999) however concluded, after reviewing literature on fall velocities of flocs, that flocs may be treated as porous, though impermeable entities.

3.7 Conclusion

The material that leaves the overflow of a dredging ship merely consists of fines (clay and silt). Clay is thus an important factor in this research. Flocculation however, probably, is not. The mud flocs that are dredged from the seabed will be fragmented due to the strong suction force in the suction pipes and the high turbulence when entering the hopper. The mixture with the clay particles can form flocs again, when released again through the overflow . Probably we are dealing with low-order flocs. The clay particles cannot reach the equilibrium flocsize as presented in Figure 3.5 due to the high settling velocity and the shortage of flocculation time. The overflow mixture often reaches the bed very quick, as will be discussed in Chapter 4. The next chapter shall also give an indication whether the particles and flocs settle at their own fall velocity or with an increased fall velocity. In the latter case it will not be possible for particles to form flocs.

An extra aspect is the fresh water/salt water effect. The material that is dredged may have been deposited or stored in a fresh water environment. The flocculation rate can be enhanced when this material is released in salt water.

Chapter 4

Sediment plumes

4.1 Introduction to plumes

The water-sediment mixture that leaves the overflow of a dredging vessel may have large ecological impacts. This depends amongst other things on the way the sediment is dispersed when leaving the overflow. Upon release from the overflow pipe, the dredging spill forms a negative-buoyant plume, which is either mixed directly with the ambient water or behaves as a density current upon impingement on the sea floor (Winterwerp, 2002). Plumes that mix directly are called passive plumes, while plumes that evolve as a density current are called dynamic plumes. The behaviour and impact of both plumes differs distinctly.

4.1.1 Dynamic plumes

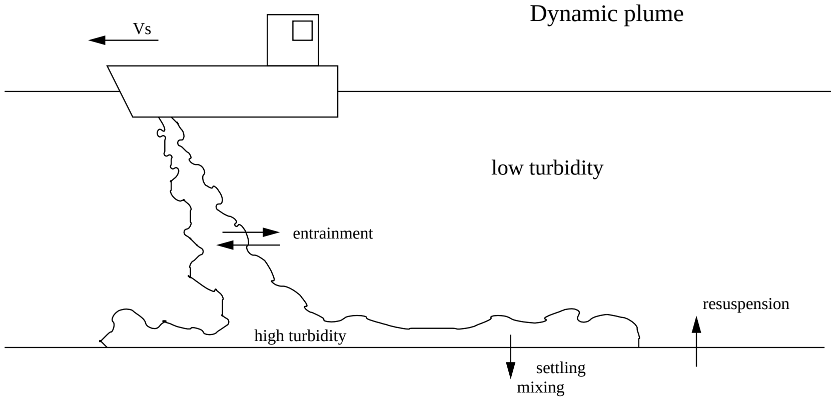

Figure 4.1: Processes in and around a dynamic plume

Dynamic plumes descend rapidly towards the seabed and then spread radially outward across the seabed as a dense plume, slowing with time and distance as the kinetic energy is spent overcoming friction. The bulk behaviour of the water-sediment mixture, rather than the settling velocity of the individual particles, is important (Winterwerp, 2002). As the settling velocity of a dynamic plume is relatively large, the zone of impact is relatively small. A deposit of fines is formed in the near vicinity of the ship. The deposit is mixed with the sediment in the bed or forms a layer on the bed. This will be discussed in sections 5.4 and 5.5. Due to currents and in the case of high orbital velocities, e.g. during rough weather conditions, the fines deposited may be resuspended, which will lead to high turbidity rates in the water column.

4.1.2 Cloud formation

A special case of a dynamic plume develops when the outflow through the overflow is not continuous; e.g. in the case of large waves that make the ship roll. Clouds of sediment, water and probably air bubbles then leave the overflow, behaving differently than a continuous density current. This is called cluster settling, convective settling or cloud formation (Scott, 1984; Winterwerp, 1999). Clouds can also form from density currents by stretching. Stretching causes a long plume or jet of water to break up in several components. An example of this is the water jet leaving a tap or the smoke plume leaving a chimney.

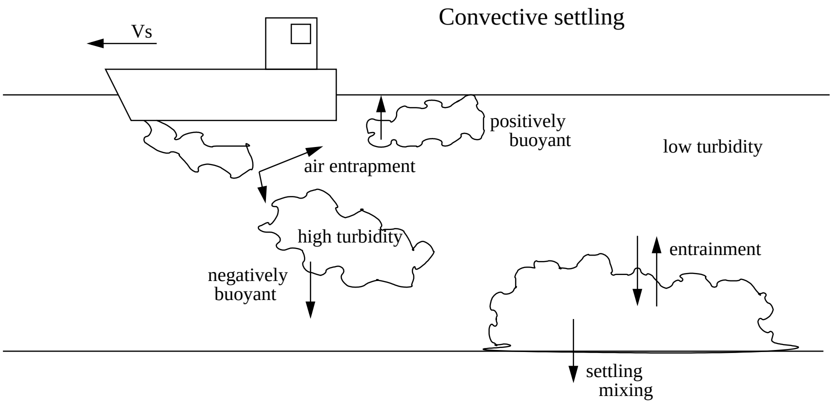

Figure 4.2: Processes in and around clouds of sediment

4.1.3 Passive plumes

Passive plumes arise due to stripping of dynamic plumes by entrainment caused by turbulence. When the current velocities are strong enough, the plume will be mixed entirely with the surrounding water. The sediment concentrations within a passive plume are thus relatively low. The fine particles may stay in the water column for several hours or even days before settling occurs, because the settling velocity is small. The zone of impact of the passive plume can be several kilometres or more and is dependent on the magnitude and direction of the currents and on the nature of the released sediment.

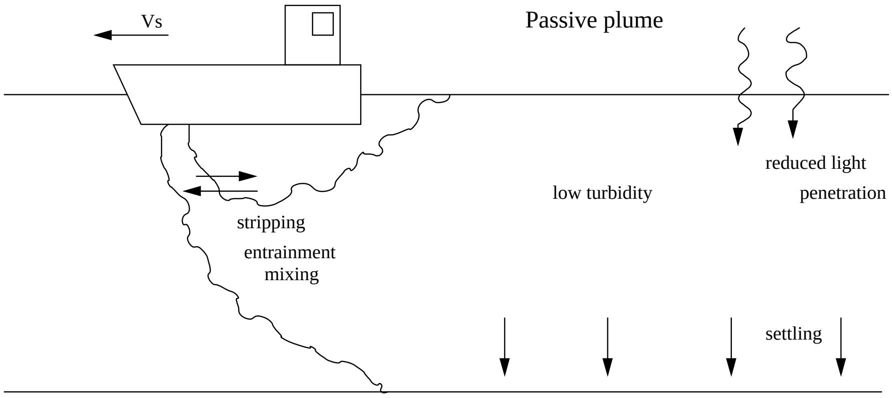

Figure 4.3: Processes in and around passive plumes

4.1.4 Classification

Winterwerp (1999) describes an experimental study on the near-field spreading of dredging spill from hopper suction dredgers in shallow water. In particular, he developed a scheme to determine whether the overflow plume is expected to mix directly with the ambient current, or whether the plume will behave as a density current on the seabed. It showed that the behaviour of sediment plumes can be described by two parameters: a bulk Richardson number:

$$R = \frac{\epsilon g d}{W^2} \tag{4.1}$$

and a velocity ratio:

$$\zeta = \frac{U}{W} \tag{4.2}$$

in which ϵ is the relative excess density of the dredging plume; d is the diameter of the overflow pipe (initial diameter of the plume); U is the velocity of the ambient water relative to the ship, sailing with or against the ambient water, and W is the outflow velocity of the plume. Experiments showed that at low ζ values and high R values, the spreading of the

Figure 4.4: A density current in still water. After Boot (2000)

overflow plume in the vicinity of the ship is driven by density currents, see for example

Figure 4.4. On the other hand, at high ζ values and low R values, the spreading of the overflow plume in the vicinity of the ship is governed by the ambient flow. In between, a transitional zone exists where both processes are important and cannot be distinguished from each other (Winterwerp, 2002). The relation between R and ζ and the corresponding zones for density currents, transition and mixing are presented in Figure 4.5.

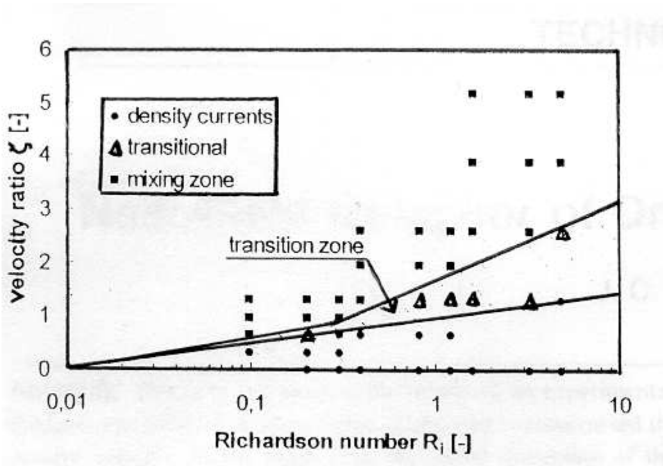

Figure 4.5: Classification of near-field dispersion of dredging spill from hopper suction dredger in shallow water. After (Winterwerp, 2002)

Hogg & Huppert (2001) carried out experiments with a cloud of heavy particulate matter being instantaneously released from either a line or a point source in a uniform ambient flow. They found the particles to be advected by the flow as well as sedimenting from it. They saw clearly that as the mean stream velocity increased, advection became relatively more important and the spreading of the sediment increased. This is the same result as is shown in Figure 4.5. An increase in velocity means an increase in ζ and a transition to the mixing zone.

4.2 Behaviour of sediment in plumes

When sediment in a plume settles with the settling velocity of single particles as given by Stokes in equation 3.1, the plume is called passive. When the bulk behaviour of sediment is more important than the behaviour of single particles the plume is called dynamic. In a passive plume the sediment concentrations are generally so low that hindered settling doesn't play a role, this in contrast to dynamic plumes. However, in both cases segregation is an important factor that needs to be discussed.

4.2.1 Hindered settling

Hindered settling is the influence of neighbouring particles on the settling velocity of an individual particle within a suspension (Winterwerp, 1999). Scott (1984) made an extensive review of hindered settling formulaes. However these were developed for massive, Euclidean particles (sand) and mostly based on Stokes' settling velocity for single particles. Therefore they cannot just be used for cohesive material.

Thacker & Lavelle (1977) define kinematic and dynamic effects that hinder settling. Kinematic effects are due to the upward flow of the fluid and to the influence of the sediment on the hydrostatic pressure. Dynamic effects are due to increases in drag force per particle by turbulence that develops at increasing concentrations, and random forces felt by particles due to asymmetries in the flow field.

Winterwerp (1999) identified seven processes that affect the settling velocity of individual particles in a suspension:

- Return flow and wake formation. Falling particles create a return flow and a wake. The fall velocity of particles in the near vicinity will be affected, decreasing the overall effective settling velocity of the suspension by a factor $(1-\phi)$, where ϕ is the volumetric concentration of mud flocs.

- Dynamic flow effect. The effect of neighbouring particles on the velocity gradients around a falling particle.

- Particle-particle collisions. Collisions between particles cause additional stresses, decreasing the effective settling velocity of the suspension.

- Particle-particle interaction. The attraction and repulsion of particles, where the attraction possibly results in flocculation.

- Viscosity. The effective viscosity increases with particle concentration. Each individual particle falls in the remainder of the suspension with increased viscosity, decreasing the effective settling velocity of all particles.

- Buoyancy or reduced gravity. Individual particles settle in the remainder of the suspension with an increased bulk density, decreasing the effective settling velocity by a factor $(1-\phi_p)$, where ϕ_p is the volumetric concentration of primary particles.

- Cloud formation or settling convection, which is discussed in chapter 4.2.2.

Hindered settling in mud suspensions normally occurs when concentrations reach over about 10 g/l. This corresponds to a volumetric concentration of many tens percents. At lower concentrations particles settle with a settling velocity defined by Stokes, as described in equation 3.1. Formulae for settling velocities in the hindered settling regime are defined differently by many authors. Most of them are based on the Richardson & Zaki (1954) formula:

$$w_s = w_{s,r}(1 - k\phi)^n \tag{4.3}$$

in which w_s is the effective settling velocity, varying with depth and/or time, $W_{s,r}$ is the constant or characteristic settling velocity in still water, $k \approx 1$ and n is a function of the particle Reynolds number: $2.5 < n < 5.5$. Richardson and Zaki derived this formula from an extensive series of sedimentation and fluidization experiments with particles of a large variety in shape and Reynolds numbers. Examples of studies that are based on the Richardson and Zaki formula are the experimental studies of (Landman & White, 1992) and the theoretical and numerical studies of (Darcovich *et al.*, 1996; Thacker & Lavelle, 1977; Buscall, 1990), from which the latter two are studies using a two-phase model.

The detailed review made by Scott (1984) was presented partly in a paper by Mandersloot *et al.* (1986). He defined all hindered settling models, theoretical and empirical, as flow field models or viscosity function models. The flow field model is based on the theory of particle-particle interactions or permeability theory. They usually account wrongly for buoyancy but obtain the correct type of response. Buoyancy is not caused by the density difference between the suspended particles and the surrounding liquid, but is the result of imbalance between pressures exerted on each of the settling units by the fluid, which has a vertical hydraulic gradient. In a suspension this gradient is determined by the suspension density and not the liquid density.

Viscosity function models are based on the superposition of the effects of buoyancy and return flow, adding a suspension viscosity term to account for particle-particle interaction. This suspension viscosity term tends to infinity for high concentrations. However the resistance to flow through a particle assembly does not become infinite at high particle concentrations. Permeability at that condition is often still substantial. Therefore viscosity function models do not work properly at very high concentrations. According to Mandersloot *et al.* (1986), invoking a suspension viscosity is physically questionable, because in hindered settling the swarm of particles descends as a whole without substantial mutual particle movement; the suspension is therefore not sheared in total. In fact, the only fluid dynamic phenomenon that can retard each particle, (compared with single particle sedimentation) is an increase in the velocity gradient at the particle surface and thus the viscous force on a particle. This increase in velocity gradient is indeed caused by the presence of other particles, forcing return flow through space between the particles.

Davis (1996) makes a summary of theoretical hindered settling function models which involve solving the low-Reynolds number equations within a fluid cell encasing a representative particle. Characteristic of these models is that the particles are assumed to be configured in an ordered array. This in contrast to functions that assume randomly distributed particles. The assumptions then made regarding the statistical structure of the suspension determine the kind of hindered settling function. For cell models

$$f(\phi) = 1 - \beta\phi^{\frac{1}{3}} \tag{4.4}$$

with f is a hindered settling function and β = 3/2 is used. For randomly distributed models

$$f(\phi) = 1 - \alpha\phi \tag{4.5}$$

with α = 6.5 is used. The latter is showing a slower linear decrease.

Winterwerp (1999) found for hindered settling of cohesive sediment flocs the following:

$$w_s = w_{s,r}\frac{(1-\phi)^m(1-\phi_p)}{1+2.5\phi} \tag{4.6}$$

In which the factor (1-ϕ) accounts for the return-flow effect and the exponent m is an empirical parameter to account for possible non-linear effects. The volumetric concentration (ϕ), is related to the sum of all fractions, i.e. $\phi = \Sigma c/c_{gel}$. C_{gel} is the gelling concentration which is the concentration where flocs become space-filling and form a network structure, called a gel, and a measurable strength builds up. Winterwerp (1999) compared this hindered settling formula with experimental results, showing a good fit as can be seen in Figure 4.6.

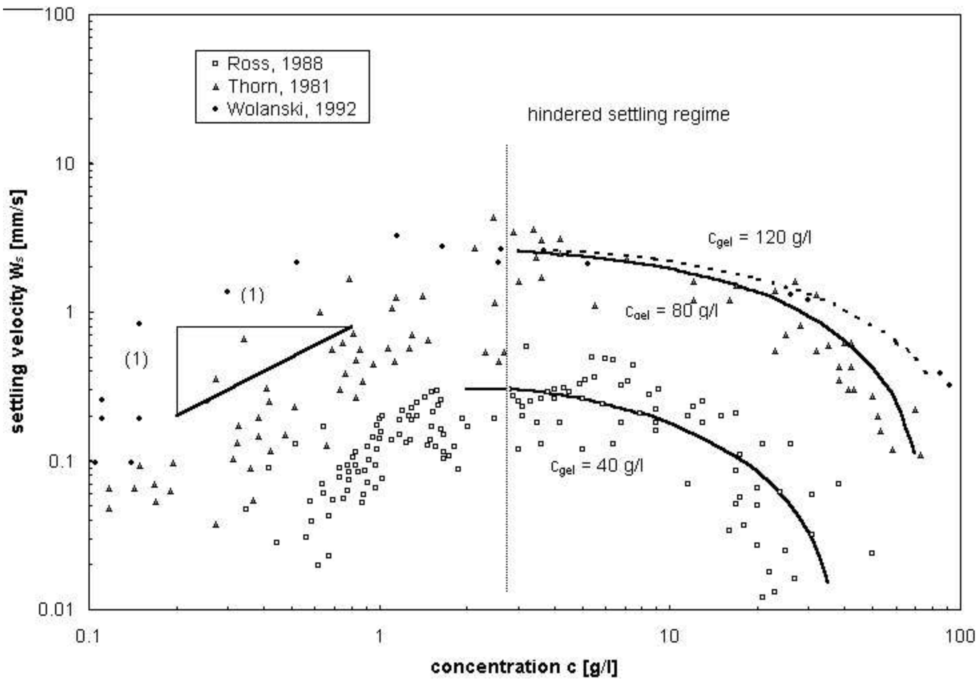

Figure 4.6: Comparison of Equation 4.6 with experimental data. After Winterwerp (1999)

The problem with many hindered settling experiments is that fall velocities are often based on visual observations of the settling of the interface. It is hard to determine an interface as the falling particles segregate and a front, middle and rear part of particles develops. Hulsey (1961) carried out experiments with glass spheres in settling tubes on the difference in fall velocity of this front and rear part. He found that in all samples, the velocity of the fastest settling particles increased and the velocity of the slowest settling particles decreased, with increasing sample weight. This he described to the fact that the front particles fall as a group, increasing fall velocity with sample weight as they fall in the wake of each other. Those fast settling particles produce more turbulent currents and eddies when the sample weight increases, which then are interfering with the slower settling particles. Hulsey (1961) states that grains falling in a turbulent system do not achieve terminal, uniform settling velocities which are always characteristic of grain dimension; rather they achieve fall velocities characteristic only of the particular system in which they fall.

Another point in accurately predicting fall velocities is that often the permeability and density of flocs is not known. Johnson *et al.* (1996) proved with experiments that fractal aggregates composed of inorganic microspheres can settle on average 4-8.3 times faster than predicted. According to Johnson *et al.* (1996) these differences are likely a consequence of the heterogeneous distribution of primary particles in a fractal aggregate. Johnson *et al.* (1996) among many others, assumes that flow through particles occurs. However, as already discussed in section 3.6 we assume that flocs may be treated as porous, though impermeable entities.

4.2.2 Convective settling

Convective settling is also referred to as a particle thermal or cloud formation. Kuenen (1968) already spoke about settling convection and the tendency of grains to cluster in groups, even after the container with the mixture had been thoroughly shaken. He stated that the suspension clouds thus formed may be either somewhat denser or more dilute than neighbouring clouds. The heavier clouds will start to sink, carrying their population of particles downwards at a higher speed than the fall velocity of individual grains. The lighter clouds are forced to flow upwards, bringing their particles along towards the top of the liquid. This kind of cloud movement has much in common with the flow of turbidity currents and Kuenen (1968) called it ”settling convection”. Presumably hindered settling is always in action where settling convection occurs, but settling convection is not a necessary accompaniment of hindered settling (Kuenen, 1968).

Winterwerp (1999) described it as particles in the wake of other particles, being dragged. The wake around a group of particles increases, catching more particles, and a cloud of settling particles is formed. Such a cloud may behave as a settling entity by itself, as a result of which the effective settling velocity of or within the suspension may increase.

According to Li (1997) the dumping of large amounts of sediment for land reclamations or dredging projects, induces a typical example of a particle thermal. This is also stated by Wolanski (1989) who observed sediment-induced buoyancy effects after dumping of dredge material. The sediment-water mixture behaved as a negatively buoyant fluid settling downwards and, on reaching the bottom, spreading laterally as a buoyant jet with on occasions a bore at its leading edge. Experimental studies on particle thermals were carried out by Nakatsuji et al. (1990) in Li (1997) and Bühler & Papantoniou (1991). Nakatsuji et al. (1990) found that the dynamic behaviour of a cloud of particles is close to thermal motion if the initial volume of the cloud is relatively large and the size of the particles is relatively small. In meteorology thermal motion is a buoyant pocket of air that rises vertically in the atmosphere owing to a steep or intense solar heating of the Earth’s surface (Whittow, 1984). In fluid mechanics it is a buoyant pocket of water, rising up or down in the water column. In contrast, particles in a cloud move independently and the motion is dominated by the balance between the buoyant force and the drag force on each particle if the volume of the cloud is relatively small and the settling velocity of the particles is relatively large.

Bühler & Papantoniou (1991) made an analysis of free, axisymmetric suspension thermals. The thermals first sunk, accelerating due to gravity, but with distance slowing due to interfacial shear. As long as the particles were contained in the cloud, it moved at about the same velocity as the fluid surrounding them, behaving essentially as if it contained the solids in dilution rather than suspension. Eventually, after slowing down enough, the velocity of the interstitial fluid reached the individual settling velocity or became smaller than that. The thermals in this final stage were dilute and had the appearance of a particle swarm or a passive plume, falling with the settling velocity of individual particles. Bühler & Papantoniou (1991) found a relationship at which distance from the source, the flow regime of a cloud of particles changes from a thermal-like motion to a motion of a swarm (passive plume) of individual particles (x_{ts}).

$$x_{ts} = \frac{1}{c_t c_s u_t}\left(\frac{B}{\rho_w}\right)^{1/2} \tag{4.7}$$

Where c_t is a constant for dilute thermals, $c_s = u_f/u_t$, u_f is the front velocity of the thermal, u_t is the terminal settling velocity of the released particles, B is the buoyancy force, defined as $B = m_s(\rho_s - \rho_w)g/\rho_s$, with m_s is the solid mass, ρ_s is the particle density and ρ_w the ambient fluid density.

Li (1997) developed a 3-D model to simulate the motion of particle thermals. Experimental data from Nakatsuji and Bühler and Papantoniou were found to agree satisfactory. Li (1997) showed that for the cases with small settling velocity, the frontal velocity is close to that of a thermal front. Also the frontal velocity of all cases converged to the settling velocity in the ultimate stage. Figures 4.7 and 4.8 show the computed (Li, 1997) density excess field

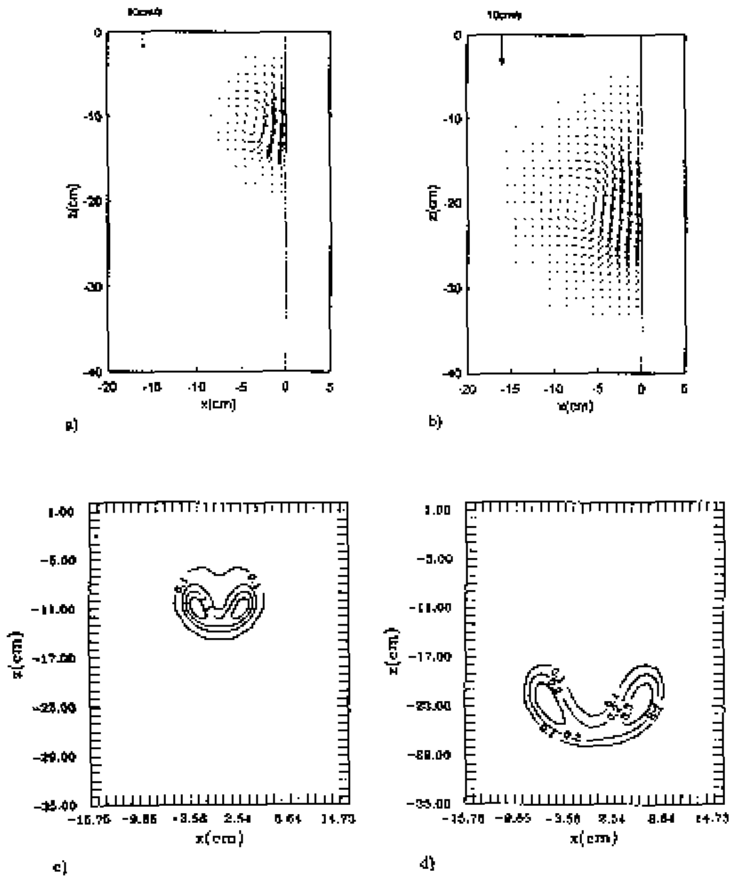

Figure 4.7: Velocity fields and density excess fields (in % of the initial value) at a section passing through the cloud centre for the case with U_t=3cm/s: a= velocity fields at time 1s; b= velocity field at time 3s; c= density excess field at time 1s; d= density excess field at time 3s. After Li (1997).

and the velocity fields at a section passing through the centroid of the cloud at different times and with different settling velocities. For the case with a "small" settling velocity (3 cm/s) (Figure 4.7), the velocity field (Figure 4.7a and b) is close to that of a thermal and displays an apparent vortex motion. The density excess field (Figure 4.7c and d) exhibits a double-peak phenomenon. For the case with a large settling velocity (14 cm/s) (Figure 4.8), the vortex motion is weak and not apparent (Figure 4.8a and b), and the double peak phenomenon in the density excess field disappears (Figure 4.8c and d) . Li (1997) explains this as the settling velocity causing the particle cloud to move away from the vortex centre before the vortex

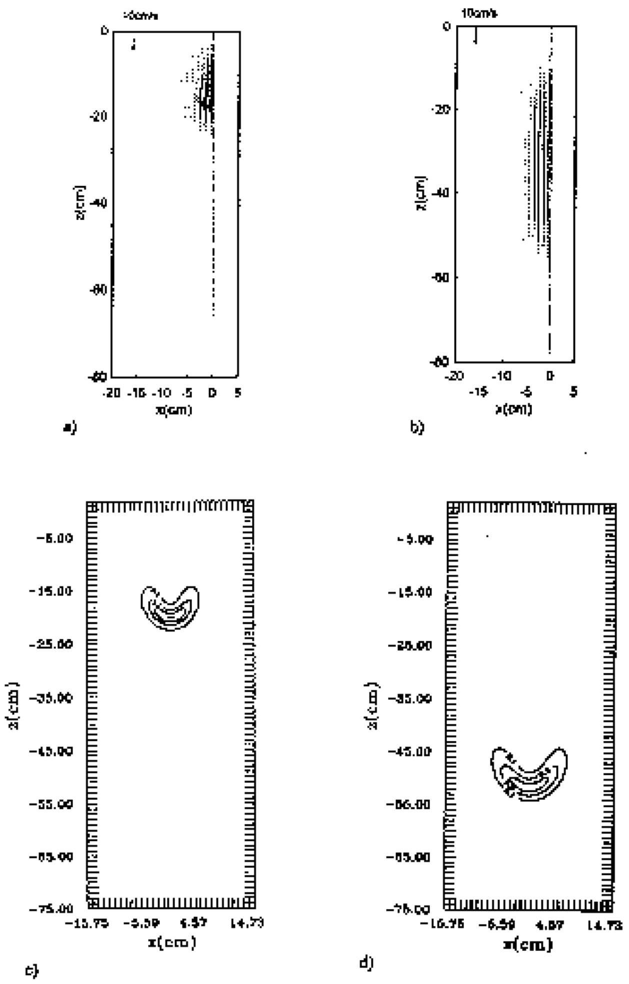

Figure 4.8: Velocity fields and density excess fields (in % of the initial value) at a section passing through the cloud centre for the case with U_t=14cm/s: a= velocity fields at time 1s; b= velocity field at time 3s; c= density excess field at time 1s; d= density excess field at time 3s. After Li (1997).

can develop strongly developed. Consequently the particles are less affected by the fluid motion, and the rate of spreading of the cloud is smaller. Li (1997) concluded that the velocity of the thermal approached the terminal velocity of the individual particles and the degree of lateral spreading of the cloud varied inversely with the magnitude of the settling velocity.

Bühler & Papantoniou (2001) distinguish two stages when a load of dense material is dumped. Provided that the particles are sufficiently small to be kept in suspension initially, the motion of the cloud is similar to that of a thermal, which as a buoyant cloud increases in size and slows down in progress. This thermal stage ends when the velocity has decreased to a value which is close to the individual settling velocity of the particles in a calm fluid, and the particles start falling out through the lower fringes of the cloud. After this transition is complete, a smooth, bowl-shaped particle swarm develops. An important difference between these two flow regimes is that in the thermal stage the fluid inside the cloud moves in unison with the particles, whilst the interstitial fluid in the swarm stage remains nearly motionless as the particles rain through (Bühler & Papantoniou, 2001). The width of the swarm increases with the cube root of the travel time and travel distance for axisymmetric swarms, and with the square root for plane ones.

Current particle cloud models employ thermal theory and an integral approach using constant entrainment (α), drag (C_D), and added mass (k) coefficients. Little is currently known about the dependence of α on material composition and the initial release conditions. Experiments on how particle size, water content and potential energy affect cloud growth within the thermal phase were carried out by Ruggaber & Adams (2000). They found that upon release, non-cohesive sediment evolved rapidly into turbulent particle clouds characterised by linear growth rates similar to classical thermals with α in the range of 0.2-0.3. Once the largest eddies approached the scale of the cloud radius, particle clouds evolved from well-mixed thermals into circulating thermals. In the circulating thermal phase, small-scale eddies were dampened when

$$N_c > 10^{-4} \tag{4.8}$$

resulting in α_2 values between 0.1-0.2. N_c is the cloud number, defined as

$$N_c = W_{s,r} \frac{\rho_a}{B}^{1/2} \tag{4.9}$$

with $W_{s,r}$ is the characteristic settling velocity in still water, B is the buoyancy and ρ_a the ambient density. Variations in water content, particle settling velocity, and potential energy, produced 10-20% variations in entrainment rate.

4.2.3 Segregation

Segregation normally occurs in mixtures of heterogeneous sediment and water. The larger particles tend to settle faster than the smaller particles, leading to a vertical gradient in grain size. The lowest region in a settling column contains all the particle species, whereas the region immediately above it is devoid of the fastest-settling specie. Each successive region contains one fewer species than the region below, with the upper region of the suspension containing only particles of the slowest-settling species (Davis, 1996), which is depicted in Figure 4.9.

Torfs *et al.* (1996) studied the occurrence of segregation in mud/sand mixtures by means of analysing data of earlier experiments done by other researchers. They found that in some

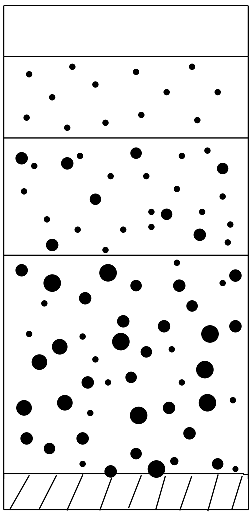

Figure 4.9: The regions that develop during the sedimentation of a mixture of three distinct species of particles. Region 1 contains all three species of particles, region 2 is devoid of the fastest settling species, and region 3 contains only the slowest settling species. After Davis (1996)

sand/mud mixtures sand had fallen through the mud matrix and was collected at the bottom of the column or layer. Figure 4.10 shows the size gradings of the bottom and top layer of two of these experiments. These size gradings indicate clear segregation between the top and the bottom of the bed for both tests. Furthermore there was increased segregation for the 66% sand tests and the bottom millimetre of the bed consisted entirely of sand (Torfs *et al.*, 1996).

In their experiment segregation occurred at low concentrations and high sand contents and resulted in a stepped profile. However they agree that segregation can also occur for 0% sand mixtures when strong, compact flocs sink to the bottom of the bed. Furthermore, for the segregated beds, the sand accumulated in a sand layer at the bottom, leaving the surface layer sand free. This is also noticeable in the field where laminated mixed beds or fining upward sequences are quite common.

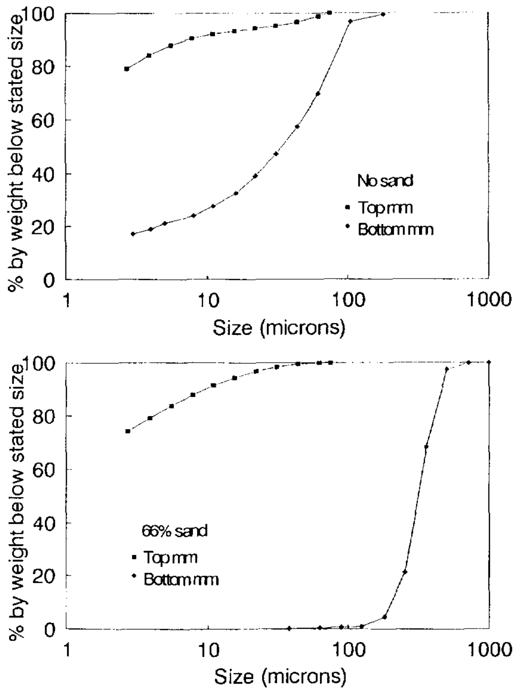

Figure 4.10: Size grading of the top and bottom millimetre of the bed after single shot experiments with Hong Kong mud. After Torfs *et al.* (1996)

4.3 Conclusion

The sand/mud mixture that leaves the overflow of a dredging ship can behave in several ways. Dynamic or passive plumes can be formed and convective settling may take place. Determination of the development of a passive or dynamic plume is possible with the classification presented in section 4.1.4.

Hindered settling is a phenomenon that occurs both in dynamic plumes as in particle thermals (convective settling). Hindered settling formulas exist for sand and for mud. However, in the case of overflow plumes, there is a need for a hindered settling formula for sand/mud mixtures.

Convective settling plumes can behave as a thermal, where the particles fall as a group, or as a swarm of particles falling at their own settling velocity. This is important to know as it determines the time the particles stay in the watercolumn. In the case of convective settling, it may be possible to determine the change from a thermal to a swarm of particles with the equations presented in section 4.2.2

Chapter 5

Sedimentation and erosion of sand/mud mixtures

The fines leaving the overflow of a hopper will eventually settle on the seabed. This will give rise to a mixture of sand and mud. Much research on the sedimentation and erosion of sand or mud has been done (Partheniades, 1980; Van Rijn, 1993). However, there is not much knowledge about the erosion and sedimentation of sand/mud mixtures. Pioneering work in this field has been done by Van Ledden & Van Kesteren (2001).

First the erosion/sedimentation of sand and mud will be discussed separately, whereafter sand/mud mixtures will be dealt with. Furthermore some factors that may influence the sedimentation and/or erosion of mud will be discussed. The details of infiltration and mixing of clay in sand beds will be dealt with in a second literature review, which will be written in a later stage of this research.

5.1 The erosion and sedimentation of sand

Particle movement will occur when the instantaneous fluid force on a particle is just larger than the instantaneous resisting force related to the submerged particle weight and the friction coefficient. The driving forces are strongly related to the local near-bed velocities. In turbulent flow conditions the velocities are fluctuating in space and time. As also particle size, shape and position are irregular, the initiation of motion is not merely a deterministic phenomenon, but a stochastic process (Van Rijn, 1993).

The Shields diagram is often used to determine the initiation of motion. In this diagram sediment starts to move when $\Theta > \Theta_{cr}$, where:

$$\Theta = \frac{u_*^2}{(s-1)gD_{50}} = \frac{\tau_b}{(\rho_s - \rho_w)gD_{50}} \tag{5.1}$$

and:

$$\Theta_{cr} = \frac{\tau_{b,cr}}{(\rho_s - \rho_w)gD_{50}} \tag{5.2}$$

With Θ is the dimensionless particle mobility parameter, Θ_{cr} is the critical dimensionless particle mobility parameter, u_* is the bed shear velocity, $s = \rho_s/\rho_w$, τ_b is the bed shear stress, $\tau_{b,cr}$ is the Shields critical bed shear stress and D_{50} is the median of the grain size distribution.

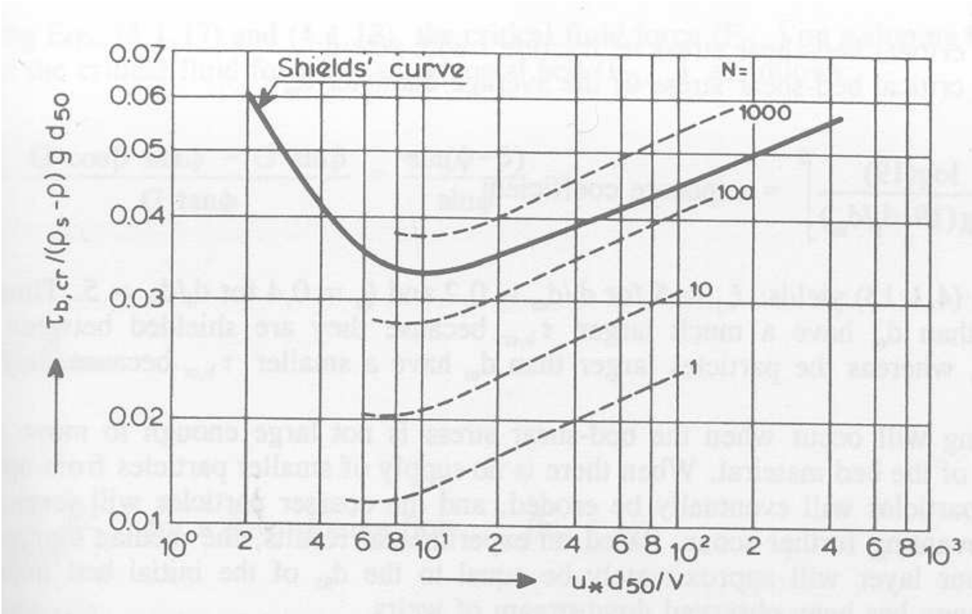

Figure 5.1: Initiation of motion for a current over a plane bed, $\phi = f(Re_*)$, N is the number of particles moving per unit area (m^2)(Van Rijn, 1993).

Formulae of erosion of sand beds under currents, waves and combined current/waves, are given in (Van Rijn, 1993). He also gives several expressions that describe the bed load transport rate q_b and several pick-up functions. The bed load transport rate can be used to determine the sand flux (F_s) from the bed into the water column. This is given by Van Ledden & Van Kesteren (2001):

$$F_s = \nabla q_b + w_s(c_a - c_s) \tag{5.3}$$

where c_a is the reference concentration and c_s the actual concentration. The pick-up rate of bed material particles is defined in terms of the number of particles (N_p) picked up from the bed per unit area and time, as (Van Rijn, 1993):

$$N_p = \eta n_r P_s = \frac{\eta}{\alpha_1 D^2} P_s \tag{5.4}$$

in which η is the fraction of susceptible particles per unit area exposed to the flow, n_r is the number of particles (at rest) per unit area, D is the particle diameter,α_1 is a shape constant (= $1/4\pi$ for a sphere) and P_s is the number of pick-ups per grain per unit time.

As soon as the sediment transport process is established, ripples and dunes are formed. The critical bed-shear stress (τ_b) over a bed consisting of bed forms is composed of a part ($\tau_b^{'}$) related to skin friction over the bed surface and another part ($\tau_b^{''}$) related to the non-uniform pressure distribution over the bed form crest and eddy region.

$$\tau_b = \tau_b^{'} + \tau_b^{''} \tag{5.5}$$

A sediment particle resting on the surface of a bed form will be set in motion by the friction force ($\tau_{b,cr}^{'}$) or by the turbulent fluctuations in the eddy region downstream of the crest

($\tau''_{b,cr}$). This means that the critical bed-shear stress ($\tau_{b,cr}$) is always larger when bed forms are present than when the bed is flat (Van Rijn, 1993).

The deposition of sand occurs when the fall velocity is larger than the lift velocity. The fall velocity of fine sand can be determined by the Stokes formula (Formula 3.1).

5.2 The erosion and sedimentation of mud

A variety of bed properties have an effect on the erosion behaviour of mud beds in natural systems. Important physical parameters for mud bed behaviour include the grain size distribution, the water content, the type of clay mineral, permeability and compressibility, degree of saturation before submergence and previous stress history. However, several biological (e.g. organic content) and chemical parameters (e.g. chlorinity, pH) are also important (Van Ledden & Van Kesteren, 2001; Partheniades, 1980).

The mud flux from the bed into the water column (F_m) is given by

$$F_m = E_m - D_m \tag{5.6}$$

Where E_m is the erosion rate of mud and D_m the deposition rate, of mud. The erosion of mud is generally described by Partheniades formula:

$$E_m = M[\frac{\tau_b}{\tau_e} - 1]H[\frac{\tau_b}{\tau_e} - 1] \tag{5.7}$$

with M is an empirical constant, H is a Heavi-side function, which equals 1 when the argument is larger than 0, and equals 0 when the argument is less or equal to 0. τ_e is the critical shear stress for erosion and τ_d is the critical shear stress for deposition. The deposition of mud is generally described by Krones formula:

$$D_m = -w_m c_m[1 - \frac{\tau_b}{\tau_d}]H[1 - \frac{\tau_b}{\tau_d}] \tag{5.8}$$

where c_m is the mud concentration. According to Partheniades, mud deposition and erosion are mutually exclusive. This means in equation 5.7 and 5.8 that the critical erosion shear stress is generally larger than the critical deposition shear stress. Winterwerp & van Kesteren (2002) however concluded that erosion and deposition of mud can occur simultaneously, leading to a deposition rate (D_m) that is given by the sediment flux at the bed, thus:

$$D = W_{s,b}c_b \tag{5.9}$$

where $W_{s,b}$ is the settling velocity of the sediment at the bed and c_b the suspended sediment concentration at the bed.

Erosion can take place by removal of individual clay particles and small clay clusters, not larger than primary particle aggregates. This is called surface erosion (Partheniades, 1980). A different type of erosion is the so called mass erosion, where erosion takes place by removal of relatively large pieces of soil. The latter applies to higher order aggregates and those formed in a highly flocculated bed with honeycombed structure freshly deposited from suspension (Partheniades, 1980). Mass erosion occurs due to large internal stresses caused when the flow or wave induced forces on the bed cause mass shear stresses which may exceed the soil strength along some small deep seated surface. Another cause can be slacking (weakening) of the material (Partheniades, 1980).

Partheniades (1980) describes experiments where the erosion rates for naturally deposited beds are not constant, but reduce with time. Sanford & Maa (2001) also described this behaviour, calling it Type I erosion, a type of erosion where τ_e increases with depth into the sediments, limiting the extent of erosion. In contrast, Type II erosion describes erosion with a single, constant value of τ_e.

Several formulations are used to determine the erosion rate (Sanford & Maa, 2001). A power law relationship, after Equation 5.7, is often used:

$$E_m = M[\tau_b - \tau_e(z)]^n \tag{5.10}$$

where E_m is the erosion rate [$ML^{-2}T^{-1}$], M is an empirical parameter, τ_b is the applied bottom shear stress, τ_e is the critical stress for erosion, z is the depth of erosion and n is an empirical parameter.

Another formulation that is often used has an exponential form:

$$E_m = \epsilon_f exp(\psi[\tau_b - \tau_e(z)]^\gamma) \tag{5.11}$$

where ϵ_f is the empirical floc erosion rate and ψ and γ are empirical constants.

However, many researchers opt for a simple linear relationship, obtained by setting n = 1 in Equation 5.10. Equation 5.11 is often used for Type I erosion, where τ_e increases with depth into the sediment and limits the extent of erosion. Equation 5.10 with n = 1 is almost always used to model Type II erosion, with a single, constant value of τ_e that does not change with depth into the sediment.

Sanford & Maa (2001) pointed out the possibility that equation 5.10, the simplest and least parameterised of the erosion formulations presented above, may be used to describe Type I as well as Type II erosion, by simply allowing τ_e to increase with depth. Many researchers have observed an increasing erosion rate after application of a step increase in stress. This points out the necessity of a linear critical stress depth profile, which can be used in Equation 5.10. Sanford & Maa (2001) explained the more rapid erosion rate just after application of a higher shear stress to the fact that the erosion rate should be increased over its constant shear stress value by a factor proportional to the time rate of change of shear stress, which is quite high at the beginning of a new shear stress step. An alternative explanation for this anomalously high erosion rate, immediately following a step increase in shear stress, is that the sudden increase in shear stress might result in brief mass erosion due to bed failure down to the level of the newly applied stress. The main result of the study of Sanford & Maa (2001) is that the character of erosion is as much a function of the time rate of change of the forcing as it is a function of the depth rate of change of τ_e. The same sediment bed can exhibit Type I erosion, Type II erosion, or something in between, depending on the nature of the forcing.

5.3 The erosion and sedimentation of sand/mud mixtures

The equations given above apply to non-cohesive sand beds or cohesive mud beds. In general these equations can't be used in the case of sand/mud mixtures. Experiments by Mitchener & Torfs (1996), Torfs *et al.* (1996) and Panagiotopoulos *et al.* (1997), have shown that a small amount of mud added to a sand bed can dramatically change the erosional properties. However Torfs *et al.* (1996) state that the erosion of cohesive sand/mud mixtures can be well described with Partheniades' erosion formula.

5.3.1 Classification of sand/mud mixtures

Non-cohesive beds have a granular structure and do not form a coherent mass. The particle size and weight are the dominant parameters for erosion. Cohesive beds form a coherent mass due to electrochemical interactions between the sediment particles. These interactions dominate the erosion behaviour; particle size and weight are of minor importance (Dyer, 1986; Raudkivi, 1990).

A sediment bed is called 'cohesive' when it exhibits a certain shear strength. It appears that for most soils a unique (decreasing) relationship exists between the remoulded shear strength and the liquidity index (LI) (Mitchell, 1993).

$$LI = \frac{w - PL}{LL - PL} \tag{5.12}$$

where w is the actual water content, LL is the liquid limit (water content that defines transition from plastic to liquid behaviour) and PL is the plastic limit (water content defining transition from solid to plastic behaviour). The difference between LL and PL is defined as the Plasticity Index (PI) which is related to the clay content by (Mitchell, 1993):

$$PI = A[C_d - n_c] \tag{5.13}$$

in which C_d is the clay content by dry weight, n_c is a offset of clay content and A is the activity of the clay. The offset according to Mitchell(1976) is about 5-10% by clay content. The liquidity index governs the transition between non-cohesive and cohesive behaviour in the following ways. First, the offset can be interpreted as a critical clay content, needed for giving a natural bed cohesive properties. Secondly the relationship between the remoulded shear strength and the liquidity index indicates that the remoulded shear strength increases with decreasing water content. Thus, the cohesiveness of a natural sediment bed not only increases with increasing clay content by dry weight, but also with decreasing water content (Van Ledden & Van Kesteren, 2001).

Another important feature for erosion behaviour is the network structure. Sand particles form a network structure if the volume fraction of sand is more than 40-50% (Merckelbach, 2000). Silt particles form a bed structure if the volume fraction relative to the volume of sand particles is more than 40-50%. In other cases, the clay fraction forms a network structure if sufficient clay is present in the sediment mixture. However, the clay content must be at least higher than the aforementioned offset for network structure (Van Ledden & Van Kesteren, 2001). Van Ledden & Van Kesteren (2001) used these parameters for cohesion and network structure to make a classification diagram (Figure 5.2).

The diagram shows the critical clay content for cohesion (set at 7%), the critical volume fractions for sand and silt (set to 40%, for volume fractions of water ϕ_w=40, 45 and 50%). These lines mark six bed types that can be distinguished. The bed types are indicated in Table 5.1 with their corresponding properties.

According to Van Ledden & Van Kesteren (2001) these six bed types are not all present in field situations. Due to the fact that the ratio between the clay and silt content in the bed in a certain system is constant, every natural system has a limited number of bed types. The properties of the proposed bed types can be estimated by using empirical relationships for the dry bed density and the remoulded shear strength. Based on these relationships and also using Allersma's empirical diagram Van Ledden & Van Kesteren (2001) made Figure 5.3 where the bed types are visualised as a function of sand content and dry bed density.

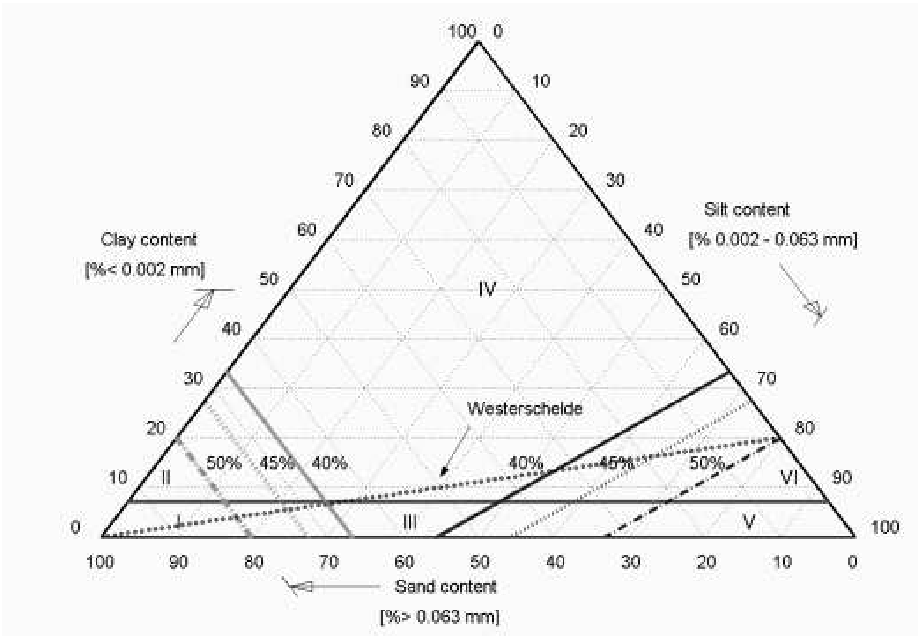

Figure 5.2: Sediment triangle with various bed types

No.	Cohesion	Network structure
I	no	sand
II	yes	sand
III	no	mixed
IV	yes	clay
V	no	silt
VI	yes	silt

Table 5.1: Bed types and their corresponding properties

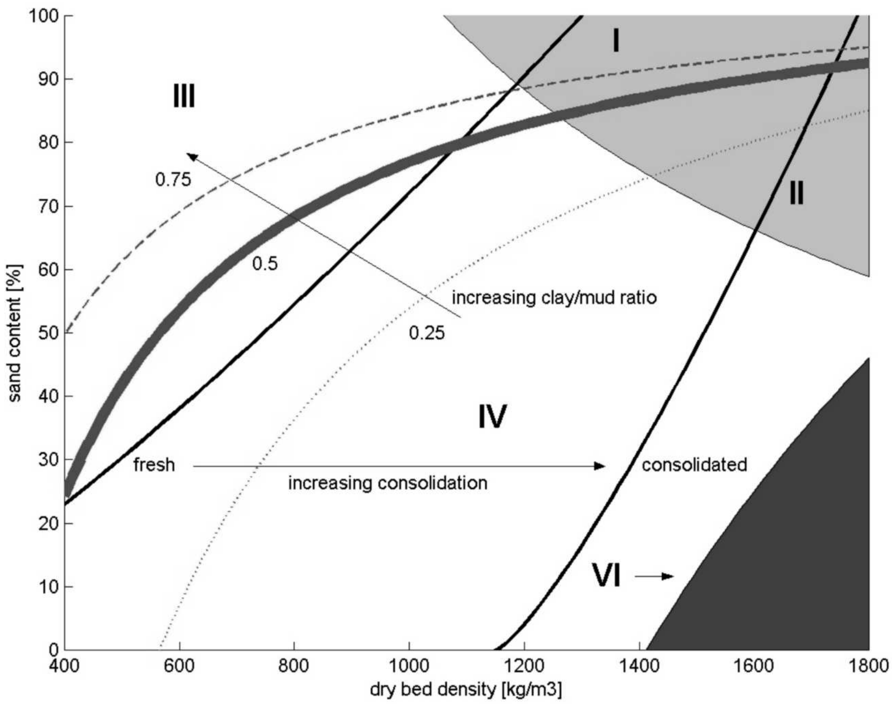

Figure 5.3: Classification diagram. After Van Ledden & Van Kesteren (2001)

The network structure is shown by the different colours: silt-dominated (black), clay dominated (white) and sand dominated (grey). Also clay/mud ratios equal to 0.25, 0.5 and 0.75 are shown. The other two lines define the area where natural combinations of sand content and dry density are found. From this figure Van Ledden & Van Kesteren (2001) draw the following conclusion. Firstly, silt-dominated bed types (V) fall outside the area in which natural combinations occur. Thus, for only very low clay/mud ratios, silt-dominated bed types (VI) will be important. Secondly, a relatively large area is covered by bed type I and IV for all clay/mud ratios. Thirdly, the importance of bed type II and III strongly depends on the clay/mud ratio. For high clay/mud ratios (>0.75), only bed type II exists, while for a low clay/mud ration (<0.25), bed type II can be neglected. For bed type III, the opposite is true.

The sediment released from a dredging ship may have a very different grain size distribution than the sediment in the sea bed. The sediment in the bed of a specific system has a constant ratio between the clay and silt content for that system. The deposition of dredging material in such a system can alter the clay/silt ratio. This can lead to a change to a cohesive or non-cohesive bed and in Figure 5.3 to more bed types that can occur.

5.3.2 Mud in sand beds, homogeneously mixed

When mud is added to a sand bed the erosion characteristics can change dramatically (Panagiotopoulos *et al.*, 1997; Mitchener & Torfs, 1996). This implies that the traditional formulae for sand transport cannot be applied directly for non-cohesive sand/mud mixtures. With an increase in the quantity of clay, sediment deposits become more plastic; the swelling, shrinkage and compressibility increase whilst the associated permeability and angle of internal friction decrease (Raudkivi, 1990).

Panagiotopoulos *et al.* (1997) tested the erosion threshold of mixed sediment deposits under the action of unidirectional currents (mean critical speeds, 4 mm above the bed, ranging from 12.4 cm/s to 18.2 cm/s) or waves (mean critical periods ranging from 2.0 s to 6.7 s, for near-bed wave amplitudes of 0.28-0.57 m) using an oscillating wave peddle in a rectangular recirculating flume. The sediment mixtures consisted of angular fine-grained quartz sands (D_{50} = 152.5 and 215 μm) and cohesive estuarine mud ranging from 0 to 50% mud content. The clay content of the mud is 36%. Their results for unidirectional flow are given in Figure 5.4. It shows that an increase in mud fraction and, subsequently, in the clay content, causes

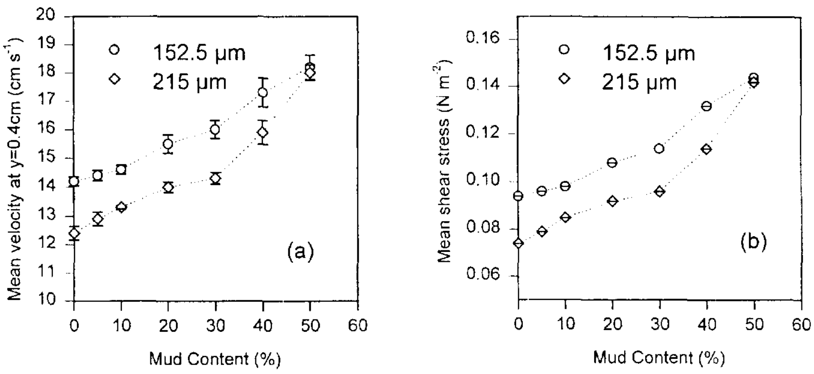

Figure 5.4: Variation in the critical mean threshold current speed (a), measured at 0.4 cm above the flume bed and the critical mean shear stress (b) with mud content, for mixed sediments, under unidirectional flow. The standard error is shown as a vertical bar and a mud content of 30% corresponds to a clay content of 11% (Panagiotopoulos *et al.*, 1997)

an increase in the critical (threshold) conditions. It seems that this increment is small at a mud content less than 30% (= 11% clay), but greater when the mud fraction lies between 30 and 50%. The sediments associated with smaller sand size are generally more difficult to erode (D_{50}= 152.2 μm). This greater resistance to erosion is explained by Panagiotopoulos *et al.* (1997) by the fact that the smaller grains are characterised by sharper corners and edges, implying higher internal friction angles. When the mud content exceeds 30% the rate of increase of the critical conditions is larger.

The results of the oscillatory flow tests of Panagiotopoulos *et al.* (1997) are shown in Figure 5.5. It shows that for mud concentrations $\leq$30%, which corresponds to a clay content of 11%, the critical maximum wave-induced velocity appears unaffected by the increasing mud concentrations. Whereas with a mud content in excess of 30% a reasonable linear and positive relationship exists between the critical maximum wave velocity and the mud content (Panagiotopoulos *et al.*, 1997). Panagiotopoulos *et al.* (1997) also found that under calmer wave conditions the effect of mud concentrations $>$ 30% is larger.

The observations of Panagiotopoulos *et al.* (1997) agree with Dyer (1986) and Raudkivi (1990) that a clay mineral content of 5-14% is high enough to dominate sediment erodibility characteristics. Mitchener & Torfs (1996) state that the mode of erosion changes from cohesionless to cohesive behaviour when small contents of mud are added to sand, with a

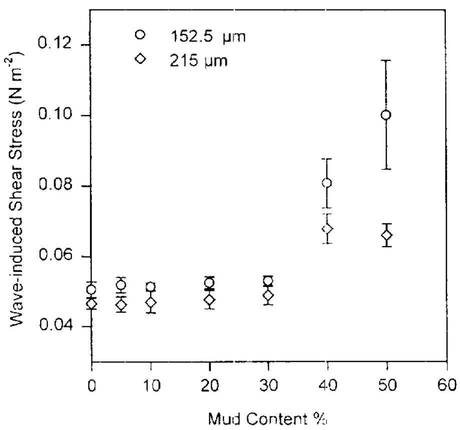

Figure 5.5: Averaged values of critical wave-induced shear stress as a function of mud content for sediment mixtures containing 152.5 μm and 215 μm sands, respectively, where 30% mud content corresponds to 11% clay content. After Panagiotopoulos *et al.* (1997)

transition occurring in the region 3% to 15% clay mineral content by weight. As the mud content (M) increases, clay minerals fill the spaces between the sand particles. At low mud contents the sand particles continue to be in contact with each other so that pivoting is the main mechanism of initiation of motion (motion due to a low angle of internal friction). Adding more mud results in infilling of the voids and in particular the spaces at either side of the contact point of two sand particles. At even higher mud contents ($M > 30\%$) a matrix of clay particles is formed which incorporates the sand and silt grains. Individual sand particles are no longer in contact with each other and movement of particles stops as the pivoting angle (the angle of internal friction) becomes too large (Panagiotopoulos *et al.*, 1997). This mechanism is shown in Figure 5.6. At these mud contents the threshold conditions are independent on the sand fraction and they solely depend on the mud fraction (Panagiotopoulos *et al.*, 1997). A consequence of these higher mud contents is a decreasing infiltration rate. Erosion may become more difficult when the infiltration rate decreases.

This is also stated by Mitchener & Torfs (1996) who carried out and reviewed annular flume and straight flume tests on artificial homogeneous and deposited beds and on undisturbed mixtures. The details of these experiments are given in their paper. They found that the erosion resistance of a sandy bed in general increases with added mud, but that the rate of increase varies for the different types of cohesive material and is dependant on the grain size of the sand. Furthermore, when more mud was added they found a change from cohesionless behaviour, where fines are washed out of the top layer and the bulk of the sediment movement occurs as bed load accompanied by ripples, to a cohesive behaviour, where aggregated clumps of material were eroded and transported as bed load. They found a change from cohesionless to a cohesive nature to take place between 3% to 15% of added mud, which is in accordance with the classification system of Van Ledden & Van Kesteren (2001).

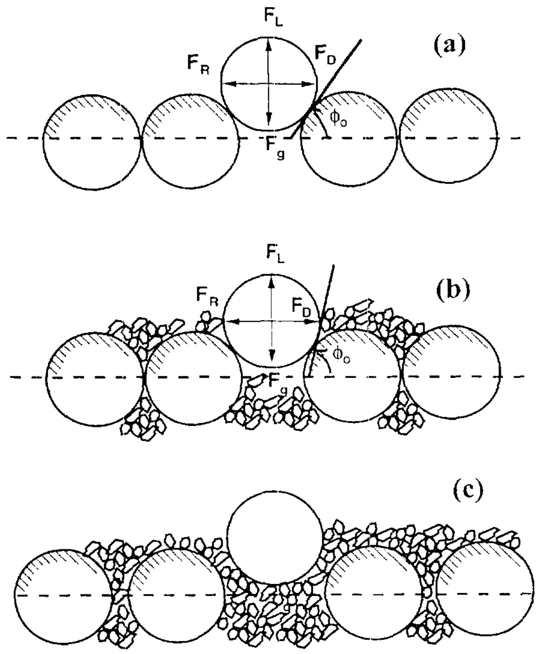

Figure 5.6: Conceptual model showing the mechanism for the initiation of sediment motion for: (a) pure sand particles; (b) sand and mud mixtures with mud content M$<$ 30%; and (c) sand and mud mixtures with mud content M$>$ 30%. (Key: ϕ_o angle of internal friction (pivoting angle); F_g weight of the particle; F_L lift force; F_D drag force; and F_R resistance force. Source Panagiotopoulos *et al.* (1997)

5.3.3 Sand in mud beds, homogeneously mixed

In addition to mud in sand beds, sand in mud beds increases the critical shear stress for erosion. It appears that the presence of the sand improves the drainage, resulting in more compaction.

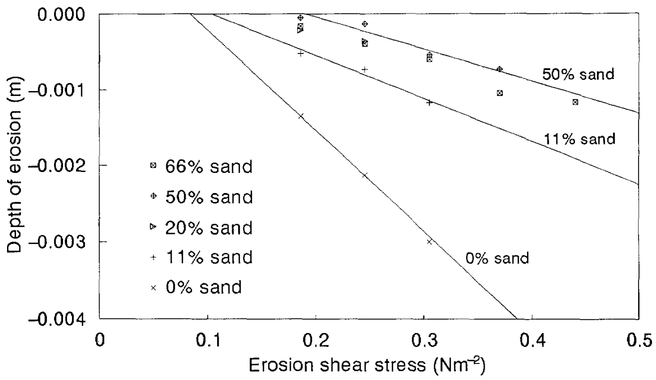

Figure 5.7: Erosion shear stress profiles obtained from annular flume erosion tests on homogeneous beds with Hong Kong mud (Mitchener & Torfs, 1996).

Mitchener & Torfs (1996) found that the presence of sand both increased the surface erosion shear stress and decreased the depth of sediment eroded at a given applied shear stress (Figure 5.7). This was based on several experiments by Ockenden and Delo (1988) on Hong Kong mud in an annular flume and by Williamson and Ockenden (1992) in a straight unidirectional current flume and in a wave flume. Another result of their study was the occurrence of an optimal ratio of sand content in a mixed bed at which the critical erosion shear stress is a maximum. The optimum sand fraction appears to lie between 50% and 70% sand by weight of sand. The optimum sand fraction and the critical shear stress are dependent on the mineralogy and grain size of the mud and sand fractions (Mitchener & Torfs, 1996).

5.3.4 Layered sand/mud mixtures

Bed deposit formed after the dumping of dredge disposal, from dredger overflow plumes or alternating periods of rough and quiet weather conditions, often have layered structures. Differential settling and sorting is considered to be the main origin of layered beds. Mitchener & Torfs (1996) found in laboratory experiments of layered beds that the erosion is characterised by erosion steps in which the erosion rate is dependent on the consolidation characteristics and strength of the layer being eroded. The upper muddy sub-layer was fist eroded and was transported mainly as suspended sediment load. A sandy sub-layer underneath the first layer was eroded as bed load, with ripple features occurring. Possible other mud layers underneath this sand layer were also found to move as bed load, as erosion took place in large lumps of mud. This is probably a result of the consolidation of the mud layer (Mitchener & Torfs, 1996).

5.3.5 Natural beds

Mitchener & Torfs (1996) conducted some test on undisturbed sediment samples in which the binding forces that naturally exist in these sediments had not been disrupted. They found the critical shear stress for erosion for these undisturbed samples to differ from artificial mixed sediment. The artificially created beds had either been mechanically mixed or deposited from suspension. For deposited beds the sediments are generally under-consolidated and have not developed the same structure that would be expected in an undisturbed natural sediment. Time related structural influences such as biological growth and chemical reactions, which affect the adhesive forces between the cohesive particles, have not had sufficient time to develop. For the under-consolidated beds there appears to exist a clear relationship between the critical shear stress and the bulk density. This may be because the beds can be considered "young" and time related structural effects are not important. Another aspect may be that the artificial beds in general do not have a stress history. Panagiotopoulos *et al.* (1997) found that a prolonged and intense stress history can increase (by a factor of 1.3-1.7) the original erosion threshold value considerably.

5.4 The effects of biological activity on the threshold of motion of sediments

Organic material is of great importance in erosion behaviour. The surface layer can become fixed due to slimes produced by diatoms and cyano bacteria, or tubes produced by sessile suspension feeders (e.g.*Lanice conchilega*) (Newell *et al.*, 1998). On the other hand bioturbation can cause the erosion shear strength to be reduced (Cadée, 2001). Communities dominated by large infauna, especially head-down deposit feeders, tend to create high rates of particle bioturbation and deep sediment mixed layers (Schaffner *et al.*, 1997) as can be seen in Figure 5.8.

Paterson (1989), among many researchers, proposed poly saccharide material produced by micro-algae (diatoms) as a mechanism for stabilisation of sediment. He carried out field experiments in two estuaries at the intertidal zone. The gravitational forces thought to govern the resistance of sublittoral sediment to erosion were not sufficient to explain the stability of intertidal sediments. Paterson (1989) found matrixes to develop at field stations that were high enough to be dry for several hours. These matrixes showed to increase the critical bed shear stress.

Grant *et al.* (1982) questioned the use of the Shields criterion to predict initial motion, as in the natural environment biogenic alteration and processing of the sediment particles and the fluid-sediment interface, takes place. They also stated the importance of the opposing influences of stabilisation and destabilisation by organisms. It is the sum of all biological and physical effects within a given sediment which determines stabilisation or destabilisation (Grant *et al.*, 1982).

Grant *et al.* (1982) carried out laboratory flume experiments on estuarine sediment samples. They found an increase in critical shear stress over the year which could be attributed to the build-up of bacteria and other metabolites (e.g. muco-polysaccharides or glyco-proteïns). In the late autumn, the biologically induced adhesion reached a maximum, which was subsequently destroyed by winter storms and ice. This biologically induced adhesion did not build up again significantly until mid-summer. Furthermore, suspension feeders like molluscs and cockles influence the erodibility of the bed. They filtrate small particles out of the water column, and deposit them on the bed as pseudofaeces (Groenewold & Dankers, 2002).

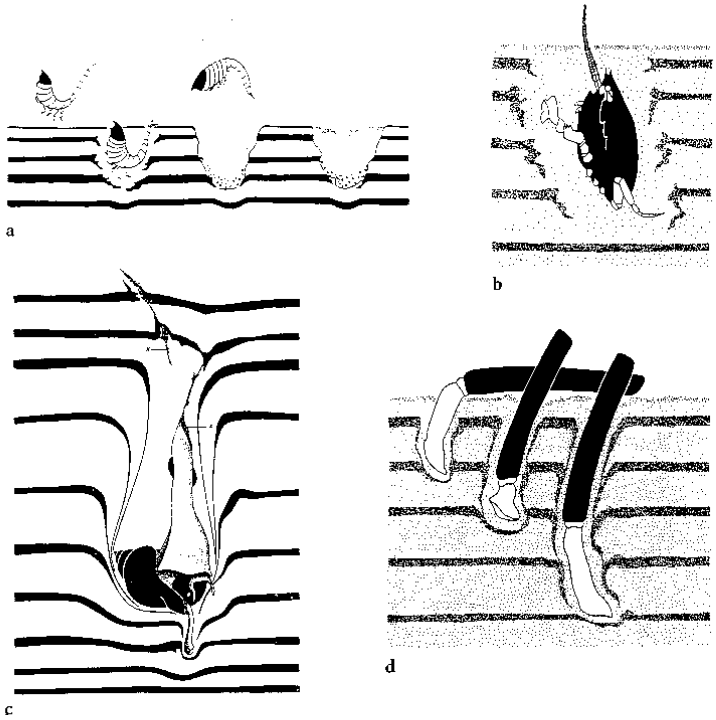

Figure 5.8: Disturbance of layered sediments by different organisms. A temporarily resting *Cumacea*; b burying crab *Corystes*; c *Buccinum* moving towards surface; and d digging *Ensis*. After Cadée (2001).

There is a big difference in fauna in the estuaries discussed above and in shelf seas as the North Sea. This difference has to do with the daily drying periods of the intertidal zone and the sediment composition, which is fine sands with mud in estuaries and sand with some mud in the North Sea. Less animals live in the bed of the North Sea. Still different species of worms and shellfish (filter feeders) are present, as well as diatoms and algae. Therefore it can be expected that the processes discussed above, bioturbation and the production of slimes etc, stabilise or destabilise sediments, as well in estuaries as in the North Sea.

5.5 The effect of waves on sand/mud beds

The erosion of mud or sand beds by wave action has been studied by several researchers (Maa & Mehta, 1987; Voulgaris *et al.*, 1995; De Wit, 1995). The application of periodic stress due to water waves over mud has a number of consequences including bed weakening, turbidity generation and surface wave attenuation (Maa & Mehta, 1987). Laboratory experiments showed that in mud beds under waves, initially a break up of bed structure occurred, possible due to a build up of excess pore pressure under waves. Later the effective stress decreased, and the bed material experienced swelling due to inter-floc rearrangement and downward fluid entrainment. Again later, the pore water escaped upward, with consequent increase in bed density (Maa & Mehta, 1987). In sand/mud mixtures this downward fluid entrainment may be able to transport fines from the upper layer downward. In the case of layered beds this may cause mixing of the sediment. On the other hand strong orbital velocities under waves can resuspend bed material whereafter the material can be transported as wash load (fines) or bed load (sand, large aggregates). This may result in increasing turbidity rates.

5.6 Conclusion

Much research has been done on the erosion and sedimentation of sand or mud. Therefore, formulae exist to determine the erosion and deposition rates of sand or mud beds. However, less is known about the erosion and deposition of sand/mud mixtures. Research has shown that it is necessary to divide sand/mud mixtures in cohesive or non-cohesive, to determine the erosion and deposition rates of sand/mud mixtures. Non-cohesive beds do not form a coherent mass where cohesive beds do. In general the transition form a non-cohesive to a cohesive bed occurs when 5-10% clay is added to a sand bed. Due to the change to a cohesive bed the critical shear strength of the bed increases significantly. In addition, the shear strength also increases when sand is added to a mud bed. Other factors that can enhance or prohibit erosion of sand/mud beds are biological activity and waves. Organic material produced by marine fauna can fix the upper layer of the bed, whereas bioturbation and waves can loosen or mix the sediment in the bed.

All together it is shown that no formulae exists to determine the erosion and deposition of sand/mud mixtures. Furthermore, the influence of biota and waves on the erosion resistance of sand/mud beds is not fully understood yet.

Chapter 6

The effect of suspended particles on ecology

Plumes from dredging activities can have an impact on vegetation, fish, shellfish, algae and other marine organisms. The increased turbidity and sedimentation, which are normally considered as temporary impacts, can become chronical in the case of large dredging projects. A distinction has to be made between turbidity in the water phase and extra sedimentation on and in the seabed. These different stages have their specific problems for different species. The most important organisms are:

- Phytobenthos, plants that live on the sea bed.
- Phytoplankton, plants that drift or float in the water column.
- Zoöbenthos, animals that live on or in the sediment. These species can be subdivided into:
  - Microbenthos, animals that feed on small plants.
  - Macrobenthos, animals that feed mostly on other animals. These are divided in:
    - Filter feeders, animals that filtrate their food from the water (e.g. mussel).
    - Deposit feeders, animals that filtrate their food from the bed sediment (e.g. shrimps).
    - Predators (e.g. crab).
- Zoöplankton, animals that float in the water, eating mostly plants.
- Fish, which can be divided into:
  - Benthic species, fish that live close to the sea bed.
  - Pelagic species, fish that live in the water column.

6.1 The water phase

Turbidity is the degree to which water contains particles that cause backscattering and absorption of light. It is a derived property of the amount of suspended material in the water column. A high turbidity may be caused by a high content of fine sediments and/or of organic particles (IADC/CEDA, 2000). Suspended sediment is a measure for the total weight of particles in suspension. Mostly the amount of suspended sediment is expressed in mg/l or ppm. The suspended sediment and the turbidity can be harmful to the bed vegetation and fauna owing to shading and burial by the released sediment. This effect only occurs when the turbidity generated is significantly larger than the natural variation of turbidity levels and sedimentation rates in the area (IADC/CEDA, 2000). The type of material is important in this case. Fine sand doesn't absorb much light, whereas clay or a coagulate of clay, organic material etc. can absorb much light.

The decreased light penetration caused by higher turbidities can affect primary production and predators that feed on sight. Primary production is a source of food for marine organisms. It stands at the basis of the food chain. A change in primary production thus will have consequences for many organisms higher in the food web. Light is the most important limiting factor for primary production by phytoplankton. Furthermore, an decrease in light penetration can give rise to a shorter or shifted bloom period for algae or shifts in species composition of phytoplankton communities or the introduction of deep-sea microbes to the surface zone (Jankowski & Zielke, 1996; Groenewold & Dankers, 2002).

The increased suspended matter has effects on the zoöplankton. Due to the increased suspended matter, which is mostly anorganic material, the ratio of organic/anorganic material decreases. Zoöplankton thus has to catch more sediment to get to the right amount of food (Douben, 1989). Jankowski & Zielke (1996) state that the higher suspended matter concentrations (more nutrients in total) can also have a positive effect on primary production.

Sight-feeders may have difficulties when suspended matter concentrations and turbidity rise. Some fish and birds may be curtailed in their possibilities to catch food. Not only by the decrease in light intensity but also by changes in the spectral composition and polarisation pattern of the light (Essink, 1999). The increased suspended matter concentrations can interfere with the gas exchange capability of fish. Higher concentrations may lead to suboptimal functioning of gills by clogging (Essink, 1999). Some fish and mobile spineless animals have shown to flee from clouds of suspended material (Groenewold & Dankers, 2002). In the case of dredging in industrially contaminated areas, the release of chemical substances, which might be absorbed in the food chain, is a severe ecological effect (IADC/CEDA, 2000).

6.2 Flora and fauna on and in the bed

A direct effect for flora and fauna living on the bed is the possible removal (by the dredger) or burial (by sediment from the plume) of its habitat. The danger of burial is very different for various species. In general sessile suspension feeders (mussel, cockles, corals) have a lower tolerance of sediment cover than mobile species and tolerance is generally greater for sedimentation of fine sand than for mud (Essink, 1999).

Zoöbenthos are animals that are living on the bed, or are shallow buried, e.g. mussels (Mytilus edulis), cockles (Cerastoderme edule) and other shellfish. They are mostly filter feeders, living on bacteria, cyano-bacteria, algae and microzoöplankton and phytoplankton, which they distract from mud. Grain size, organic fraction and the state of decomposal of the organic material are of high importance for filter feeders (Groenewold & Dankers, 2002). Most filter feeders prefer small particles like silt and clay to distract their food from. A lot of them are even specialised in certain grain sizes (Groenewold & Dankers, 2002). In the case of filter feeders it is possible that higher suspended sediment concentrations than normal, can cause obstruction and clogging of the filter apparatus (Essink, 1999; Groenewold & Dankers, 2002).

In contrast to filter feeders that collect their food from suspension, deposit feeders collect food from organic material on or in the bed. A lot of bivalves however can collect food from both suspension and seabed. These groups may benefit from increasing suspended sediment concentrations because the total organic fraction increases (Groenewold & Dankers, 2002; Douben, 1989).

Furthermore increasing turbidity causes limiting growth of phytobenthos and the increased fine sediment fraction in or on the seabed can possibly change the bed structure. In that case the habitat may not be suitable anymore for autochthon species.

6.3 Conclusion

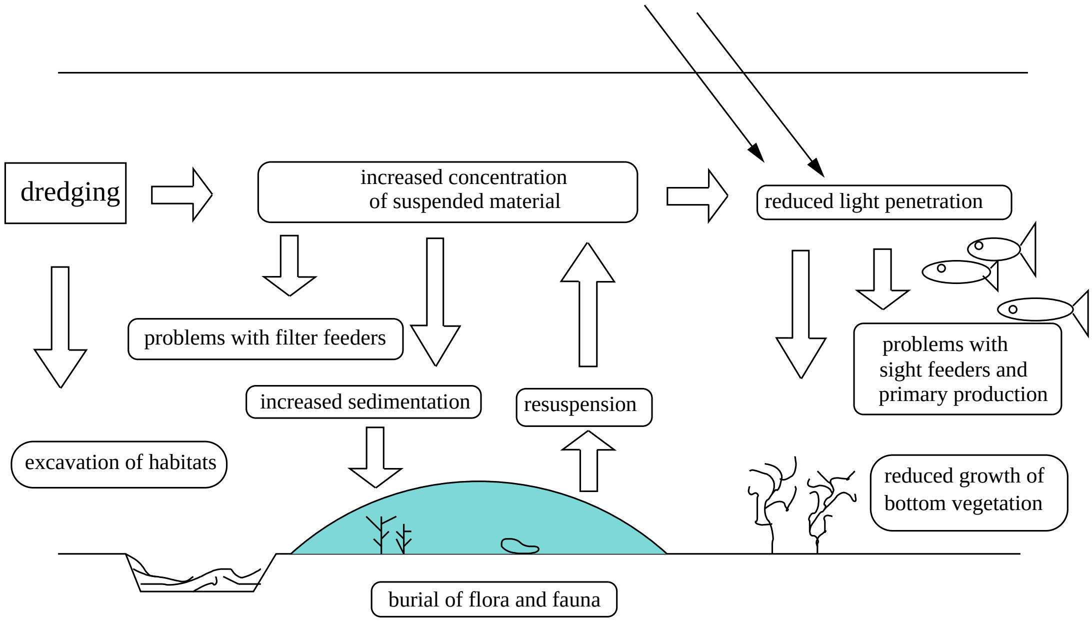

Figure 6.1: Impact of dredging on ecology

Dredging in estuarine and coastal waters may lead to increased turbidity, higher suspended matter concentrations and enhanced sediment deposition . This mainly affects primary production by phytoplankton, performance of visual predators, and growth and survival of benthic organisms as is shown in Figure 6.1. However it is not understood yet, how large this impact is and whether it results in real problems. The circumstances in the sea and on and in the bed may change, but it is not clear if and how it will affect the flora and fauna in this region. The tolerance levels of different species of plant and animals differ from each other. Therefore some species may profit from increased sedimentation or suspended matter concentrations, whilst others do not survive a slight change in living environment. An important aspect is the kind of material that is released into the water. Clay particles together with organic material can form large coagulates that absorb a lot of light, while the organic material is also a source of food. In contrast a same weight of sand particles absorbs almost no light.

Chapter 7

Conclusions and recommendations

This report describes the results of a literature survey on the mid-field mud dispersion from dredging ships. The goal of this research is to determine the fate of the sediments that are released during dredging activities.

During the dredging process, suction pipes bring a mixture of sand, mud and water into the hopper. In the hopper the larger particles settle on the bed, while the excess water and fine sediments flow through the overflow pipes into the sea. In the water, the sediment mixes more or less with the surrounding water and finally settles on the bed. Other sources of input of fine sediment in the water are the dredging process itself (suction forces on the bed), breaching of the bed material, and loss during the travelling and during the release of the hopper material at its destination. This study focuses on the mid-field behaviour of overflow losses.

The water/sediment mixture leaves the overflow as a plume. A distinction can be made between passive plumes and dynamic plumes. Passive plumes mix with the surrounding water as soon as they leave the overflow. As a result these plumes have low concentrations of suspended sediment, low settling velocities, and can travel over a long distance. In contrast, dynamic plumes flow as a density current towards the bed. They maintain a high concentration and most of the material will settle in the near vicinity of the dredging ship. Whether a plume will develop as a passive or dynamic plume can be determined with the formulations given in section 4.1.4.

The environmental impact from dredging activities can be large. The water/sediment mixture that leaves the overflow causes a high turbidity in the watercolumn or just above the bed, depending on the type of plume. Many sea organisms suffer from this high turbidity, either because of reduced light penetration or because of the large amounts of suspended matter. The subject of increased turbidity will be dealt with in the ONL/FLYLAND and the TASS project, which are presently being executed in the Netherlands. The main focus of this midfield dispersion project however, will lie on the sea/bed interaction and the environmental impact of this interaction.

The kind of sea/bed interaction and environmental impact depends on the type of plume. Dynamic plumes settle fast towards the bed, have high sediment concentrations, and processes like hindered settling and segregation play a role in these plumes. However, there is not much known about the hindered settling and segregation of sand/mud mixtures that leave an overflow.

A special case of a dynamic plume is a convective settling plume. In this case the turbidity current has broken up into several clouds that exist of a mixture of water and sediment. These clouds can be divided into thermals and swarms. In a thermal the sediment and water move in unison with each other, while in a swarm the water remains motionless and the particles fall through. The settling velocity of particles in a swarm is smaller and the amount of lateral spreading is larger. At a certain distance from the dredging ship a thermal always changes to a swarm. This distance can be determined with the formulation given in section 4.2.2.

The sediment from dynamic and passive plumes settles on the bed and mixes with the seabed sediments. Possibly waves, with the pressure they exert on the bed, cause this mixing. Other processes like migrating bed forms, bioturbation and pressure induced by bedforms, may also play a role. Almost nothing is known about these processes in association with the mixing of fine material. Furthermore, resuspension of the settled material, for instance during storm periods, can lead again to fine material, and thus an increased turbidity, in the water column. This subject is dealt with in other research projects.

This literature review has pointed out that knowledge is lacking on hindered settling and segregation of sand/mud mixtures and on the infiltration and mixing of fine sediment into the sea bed. Therefore these subjects will be the main focus of further research. Hindered settling experiments with clay minerals and a mixture of sand and clay minerals, will be carried out in the Laboratory of Fluid mechanics at the TUDelft. The results of these experiments shall be compared with 1DV-model results, in order to determine the suitability of this model for sand/mud mixtures at hindered settling concentrations.

The infiltration and mixing of fine sediment into the bed material shall also be tested with laboratory experiments. A circular flume and a wave flume are present and can be used to determine the effect of currents, waves, bed forms and perhaps biological activity on the mixing of the sediment. However, first a supplementary literature review on the sea/bed exchange is necessary.

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List of symbols

Roman symbols

A	Activity of clay
B	Buoyancy
C	Volume concentration
C_d	Clay content by dry weight
C_i	Inflow volume concentration
C_m	Mud concentration
C_o	Outflow volume concentration
C_v	Concentration in a hopper
c	Suspended sediment concentration by mass
c_a	Reference concentration
c_b	Suspended sediment concentration at the bed
c_{gel}	Gelling concentration
c_s	Actual concentration
c_t	Constant for dilute thermals
cu	Grain size uniformity (D_{60}/D_{10})
D	Particle diameter
D_m	Deposition rate of mud
D_p	Diameter primary mud particles
D_{50}	Median of the grain size distribution
d	Diameter of an overflow pipe
E_m	Erosion rate of mud
e_c	Aggregation efficiency
F_m	Mud flow from the bed into the water column
F_s	Sand flux
f	A hindered settling function
G	Dissipation parameter
g	Acceleration of gravity
H	Heavi-side function
h_s	Height of the bed in a hopper
i	Inflow

LL	Liquid limit
M	Empirical parameter
m_s	Solid mass
N_c	Cloud number
N_p	Number of particles picked up from the bed per unit area and time
n	Exponent in hindered settling formula by Richardson and Zaki
n_c	Offset of clay content
n_f	Fractal dimension of mud flocs
n_r	Number of particles (at rest) per unit area
o	Outflow
OV	Overflow losses
OV_{cum}	Cumulative overflow flux
OV_{flux}	Overflow flux
PI	Plasticity Index
PL	Plastic limit
P_s	Number of pick-ups per grain per unit time
Q	Discharge
Q_{ave}	Average discharge
Q_i	Inflow discharge
Q_o	Outflow discharge
q_b	Bed load transport rate
R	Richardson number
Re_p	Particle Reynolds number
s	Relative density (ρ_s/ρ_w)
U	Velocity of ambient water relative to the ship
u_f	Front velocity of a thermal
u_t	Terminal settling velocity of released particles
u_*	Bed shear velocity
W	Outflow velocity of the plume
$W_{s,b}$	Settling velocity at the bed
$W_{s,max}$	Maximal settling velocity
$W_{s,r}$	Characteristic settling velocity in still water
w	Actual water content
w_s	Effective settling velocity varying with depth and/or time
$w_{s,r}$	Settling velocity of mud floc in still water
x_{ts}	Distance from source where flow regime changes from a thermal to a swarm
z	Depth of erosion

Greek symbols

α	Shape factor sediment
β	Shape factor sediment
γ	Empirical parameter
ϵ	Relative excess density of a dredging plume
ϵ_f	Empirical floc erosion rate
ζ	Velocity ratio
η	Fraction of susceptible particles per unit area exposed to the flow
μ	Dynamic viscosity
ρ_a	Ambient density
ρ_s	Density of primary sediment particles
ρ_w	Density of water
τ_b	Bed shear stess
$\tau_{b,cr}$	Critical bed shear stress
τ_d	Critical shear stress for deposition
τ_e	Critical shear stress for erosion
θ	Dimensionless particle mobility parameter
θ_{cr}	Critical dimensionless particle mobility parameter
ϕ	Volumetric concentration
ψ	Empirical parameter